Mauro Anselmino
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The single spin asymmetry A_N in $l\, p^\uparrow \to h\, X$ processes

work in preparation with:

M.A, M. Boglione, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin

trying to answer some questions:

SSA and TMDs: from physical intuition to formalism

two scale (Q^2, $k_\perp$) processes - factorization

(SIDIS, D-Y, dijets, ...)

one scale (P_T) processes: factorization ?

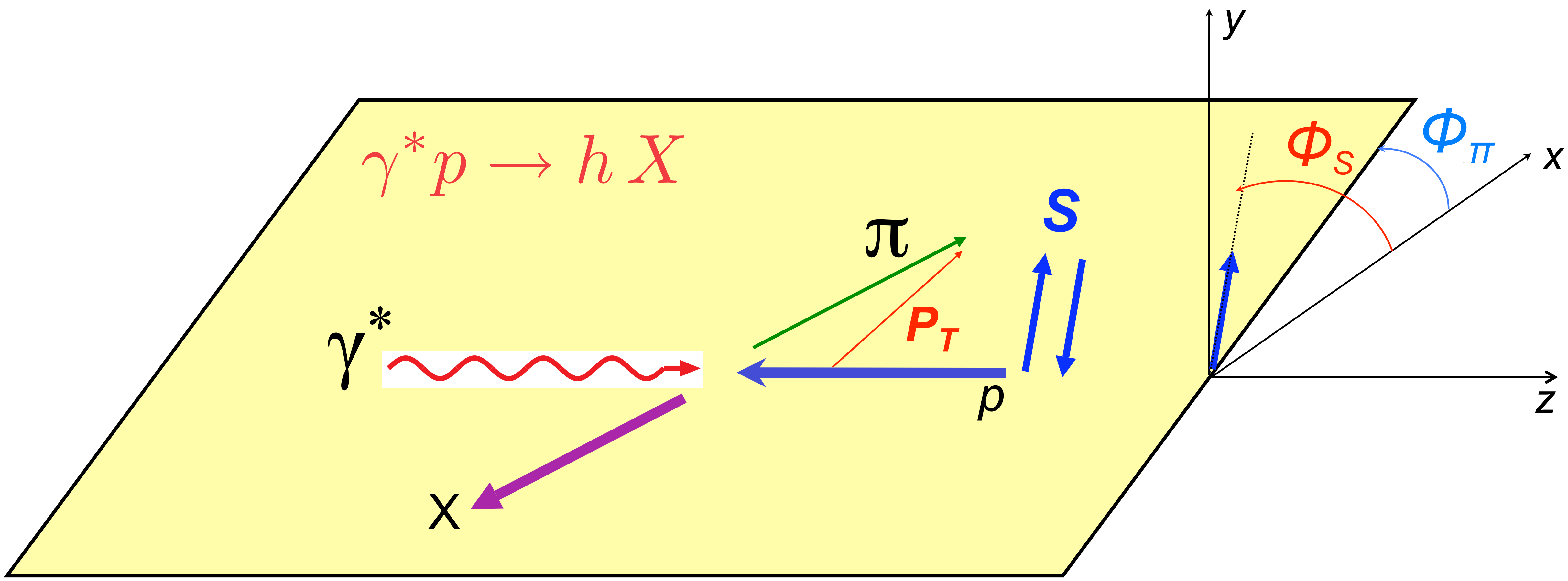
universality of TMDs ?

phenomenological test: $lp^\uparrow \to hX$

no conclusion ....

Transverse single spin asymmetries experimentally observed in SIDIS

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

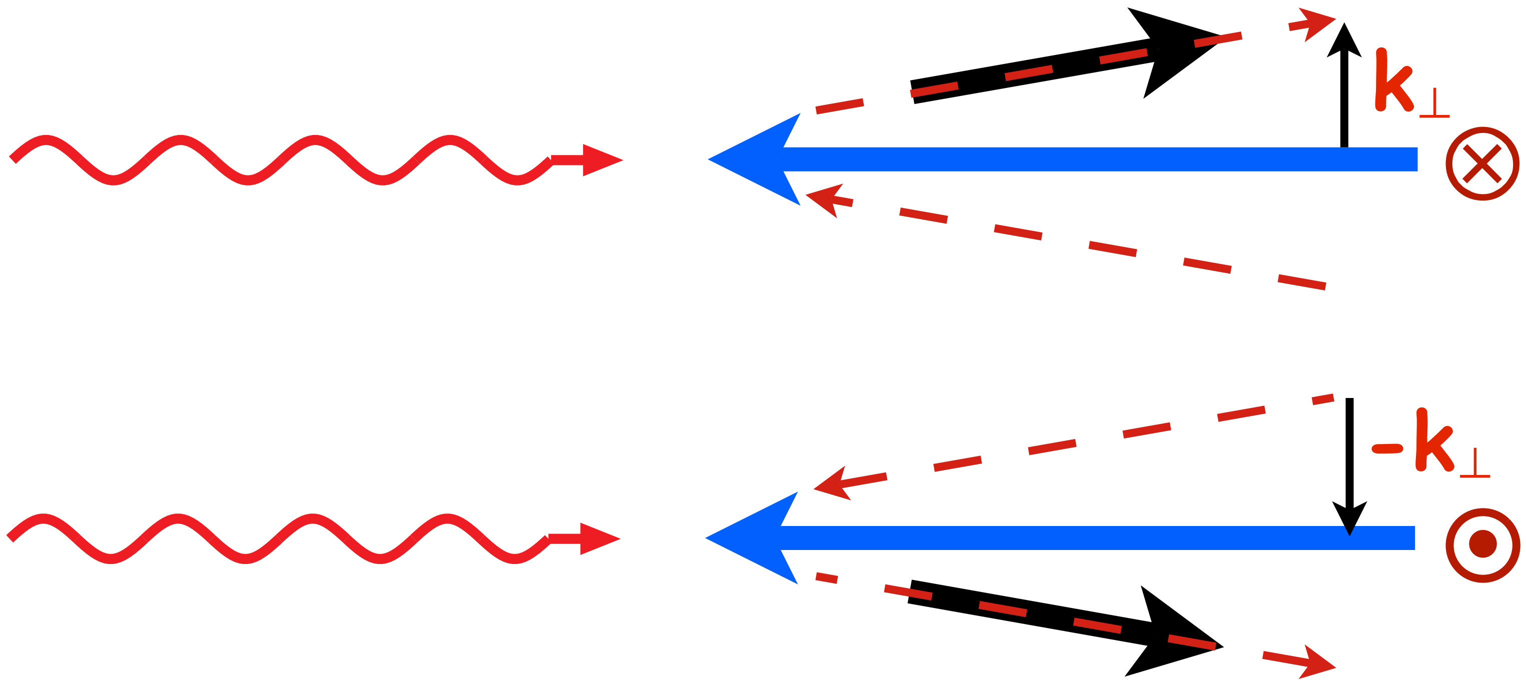


$$A_N \propto \boldsymbol{S} \cdot (\boldsymbol{p} \times \boldsymbol{P}_T) \propto P_T \sin(\Phi_\pi - \Phi_S) \qquad \gamma^* - p \text{ c.m. frame}$$

large Q^2: the virtual photon explores the nucleon structure

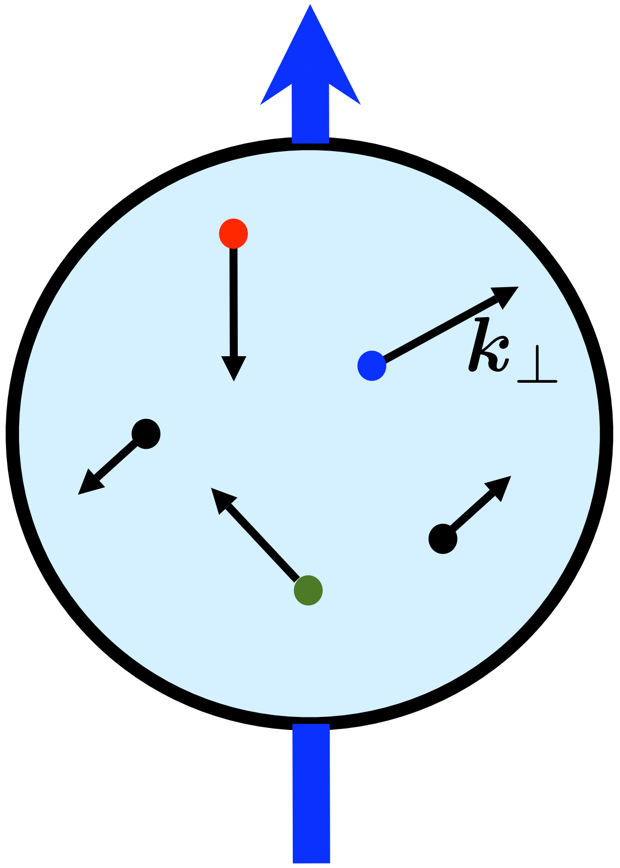
in collinear configurations there cannot be (at LO) any P_T

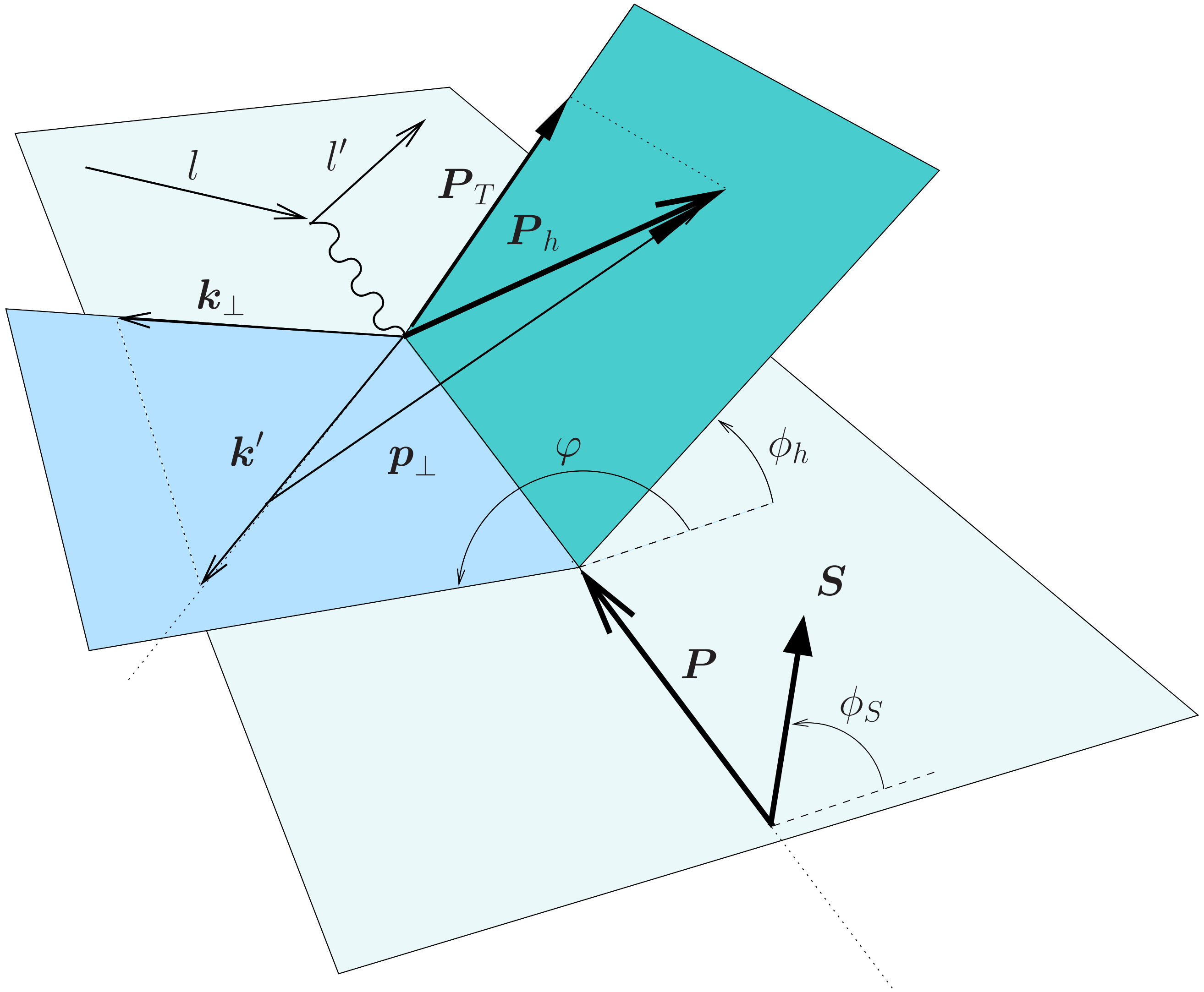
simple physical picture for Sivers effect



$$P_T \sim k_\perp$$

the large Q^2 virtual photon "sees" the spin-$\mathbf{k}_\perp$ correlation





SIDIS in parton model with intrinsic motion

$$\mathrm{d}^6\sigma \equiv \frac{\mathrm{d}^6\sigma^{\ell p^\uparrow \to \ell h X}}{\mathrm{d}x_{_B}\,\mathrm{d}Q^2\,\mathrm{d}z_h\,\mathrm{d}^2\boldsymbol{P}_T\,\mathrm{d}\phi_S}$$

$$\boldsymbol{p}_\perp \simeq \boldsymbol{P}_T - z_h\,\boldsymbol{k}_\perp$$

$$x_{_B} \simeq x \qquad z_h \simeq z$$

factorization holds at large Q^2, and $P_T \approx k_\perp \approx \Lambda_{\rm QCD}$

Two scales: $P_T \ll Q^2$

$$\mathrm{d}\sigma^{\ell p \to \ell h X} = \sum_q f_q(x, \boldsymbol{k}_\perp; Q^2) \otimes \mathrm{d}\hat{\sigma}^{\ell q \to \ell q}(y, \boldsymbol{k}_\perp; Q^2) \otimes D_q^h(z, \boldsymbol{p}_\perp; Q^2)$$

(Collins, Soper, Ji, J.P. Ma, Yuan, Qiu, Vogelsang, Collins, Metz)

SIDISLAND

$$
\begin{aligned}
\frac{d\sigma}{d\phi} = {} & F_{UU} + \cos(2\phi)\, F_{UU}^{\cos(2\phi)} + \frac{1}{Q}\, \cos\phi\, F_{UU}^{\cos\phi} + \lambda\, \frac{1}{Q}\, \sin\phi\, F_{LU}^{\sin\phi} \\
& + S_L \left\{ \sin(2\phi)\, F_{UL}^{\sin(2\phi)} + \frac{1}{Q}\, \sin\phi\, F_{UL}^{\sin\phi} + \lambda \left[F_{LL} + \frac{1}{Q}\, \cos\phi\, F_{LL}^{\cos\phi} \right] \right\} \\
& + S_T \left\{ \sin(\phi - \phi_S)\, F_{UT}^{\sin(\phi-\phi_S)} + \sin(\phi + \phi_S)\, F_{UT}^{\sin(\phi+\phi_S)} + \sin(3\phi - \phi_S)\, F_{UT}^{\sin(3\phi-\phi_S)} \right. \\
& + \frac{1}{Q} \left[\sin(2\phi - \phi_S)\, F_{UT}^{\sin(2\phi-\phi_S)} + \sin\phi_S\, F_{UT}^{\sin\phi_S} \right] \\
& \left. + \lambda \left[\cos(\phi - \phi_S)\, F_{LT}^{\cos(\phi-\phi_S)} + \frac{1}{Q} \left(\cos\phi_S\, F_{LT}^{\cos\phi_S} + \cos(2\phi - \phi_S)\, F_{LT}^{\cos(2\phi-\phi_S)} \right) \right] \right\}
\end{aligned}
$$

many spin asymmetries

$$d\sigma(\boldsymbol{S}) \neq d\sigma(-\boldsymbol{S})$$

$F_{S_B S_T}^{(\ldots)}$ contains the TMDs

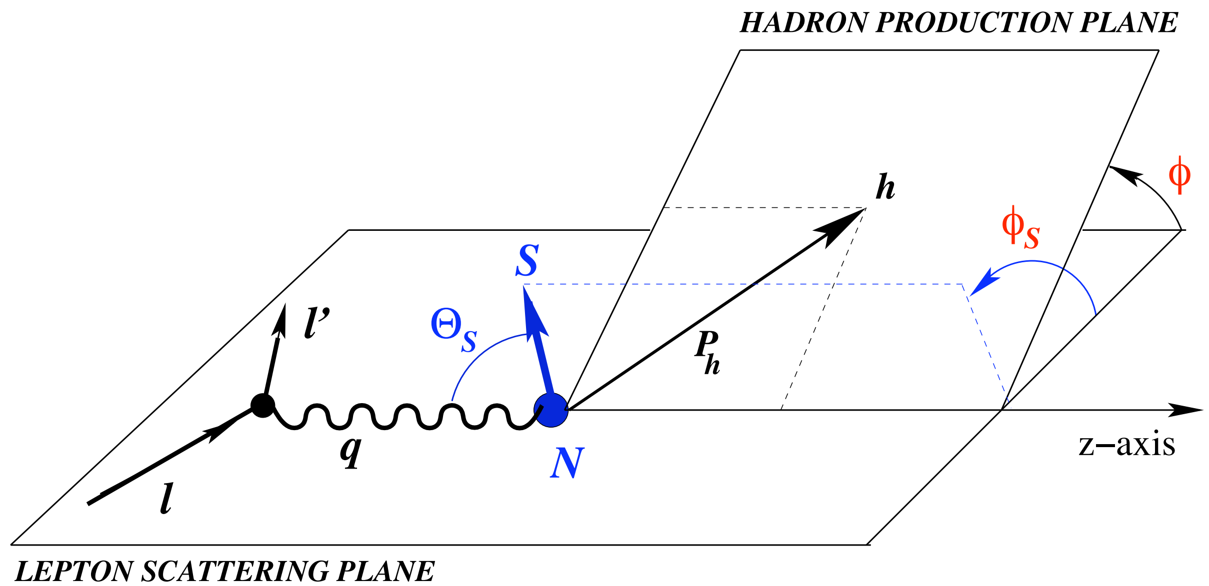
Kotzinian, **NP B441** (1995) 234

Mulders and Tangermann, **NP B461** (1996) 197

Boer and Mulders, **PR D57** (1998) 5780

Bacchetta et al., **PL B595** (2004) 309

Bacchetta et al., **JHEP 0702** (2007) 093



$$F_{UU} \sim \sum_a e_a^2 \, f_1^a \otimes D_1^a \qquad F_{LT}^{\cos(\phi-\phi_S)} \sim \sum_a e_a^2 \, g_{1T}^{\perp a} \otimes D_1^a$$

$$F_{LL} \sim \sum_a e_a^2 \, g_{1L}^a \otimes D_1^a \qquad F_{UT}^{\sin(\phi-\phi_S)} \sim \sum_a e_a^2 \, f_{1T}^{\perp a} \otimes D_1^a$$

chiral-even TMDs

$$F_{UU}^{\cos(2\phi)} \sim \sum_a e_a^2 \, h_1^{\perp a} \otimes H_1^{\perp a} \qquad F_{UT}^{\sin(\phi+\phi_S)} \sim \sum_a e_a^2 \, h_{1T}^a \otimes H_1^{\perp a}$$

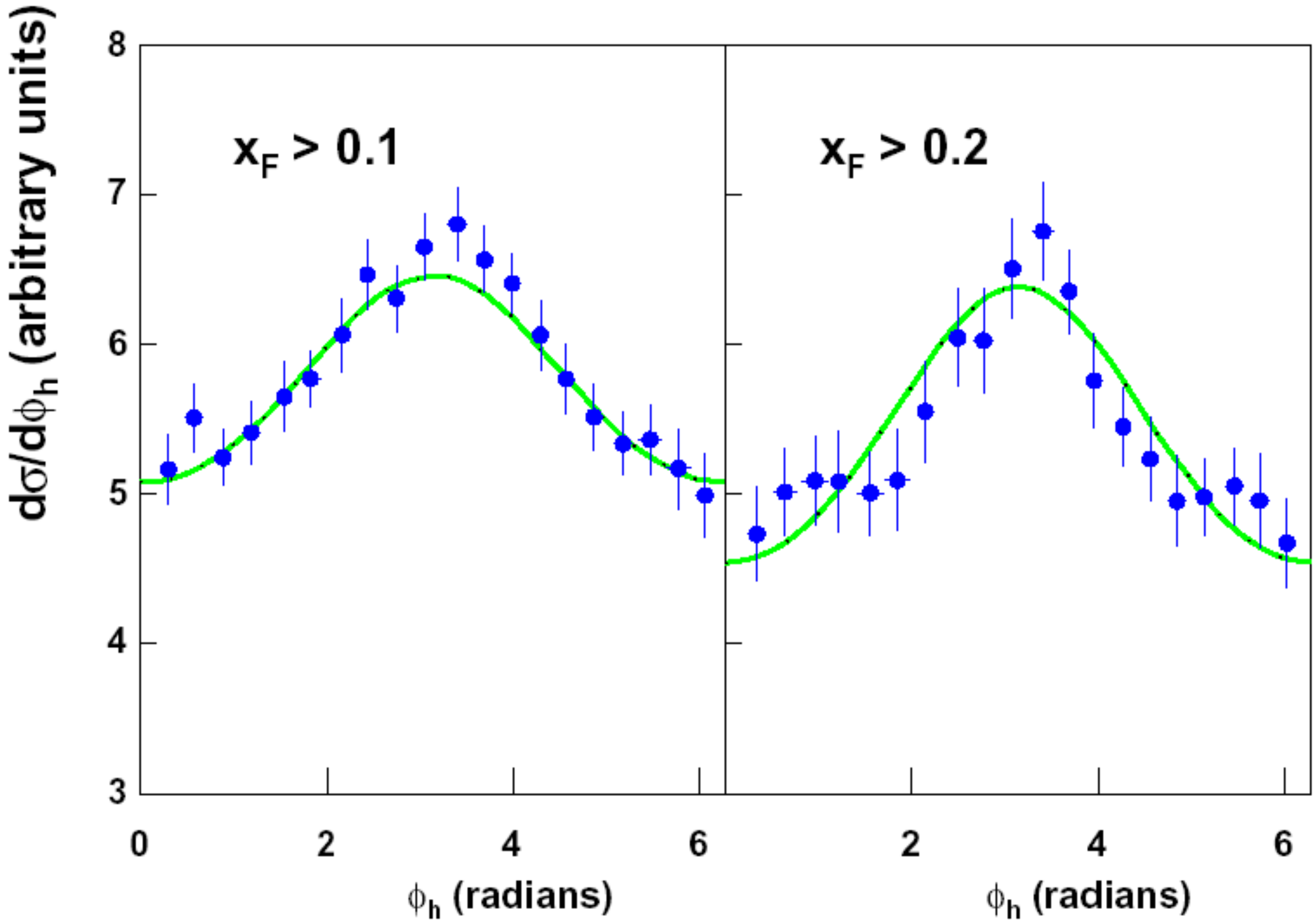
$$F_{UL}^{\sin(2\phi)} \sim \sum_a e_a^2 \, h_{1L}^{\perp a} \otimes H_1^{\perp a} \qquad F_{UT}^{\sin(3\phi-\phi_S)} \sim \sum_a e_a^2 \, h_{1T}^{\perp a} \otimes H_1^{\perp a}$$

chiral-odd TMDs

$$\frac{1}{Q} \cos\phi \, F_{UU}^{\cos\phi} \sim f_1^q \otimes D_1^q \otimes \mathrm{d}\hat{\sigma} + \left(h_1^{q\perp} \otimes H_1^{q\perp} \otimes \mathrm{d}\Delta\hat{\sigma} \right)$$

Cahn kinematical effects

Avakian, Efremov, Schweitzer, Metz, Teckentrup, arXiv:0902.0689



$\cos\Phi_h$ dependence induced by quark intrinsic motion

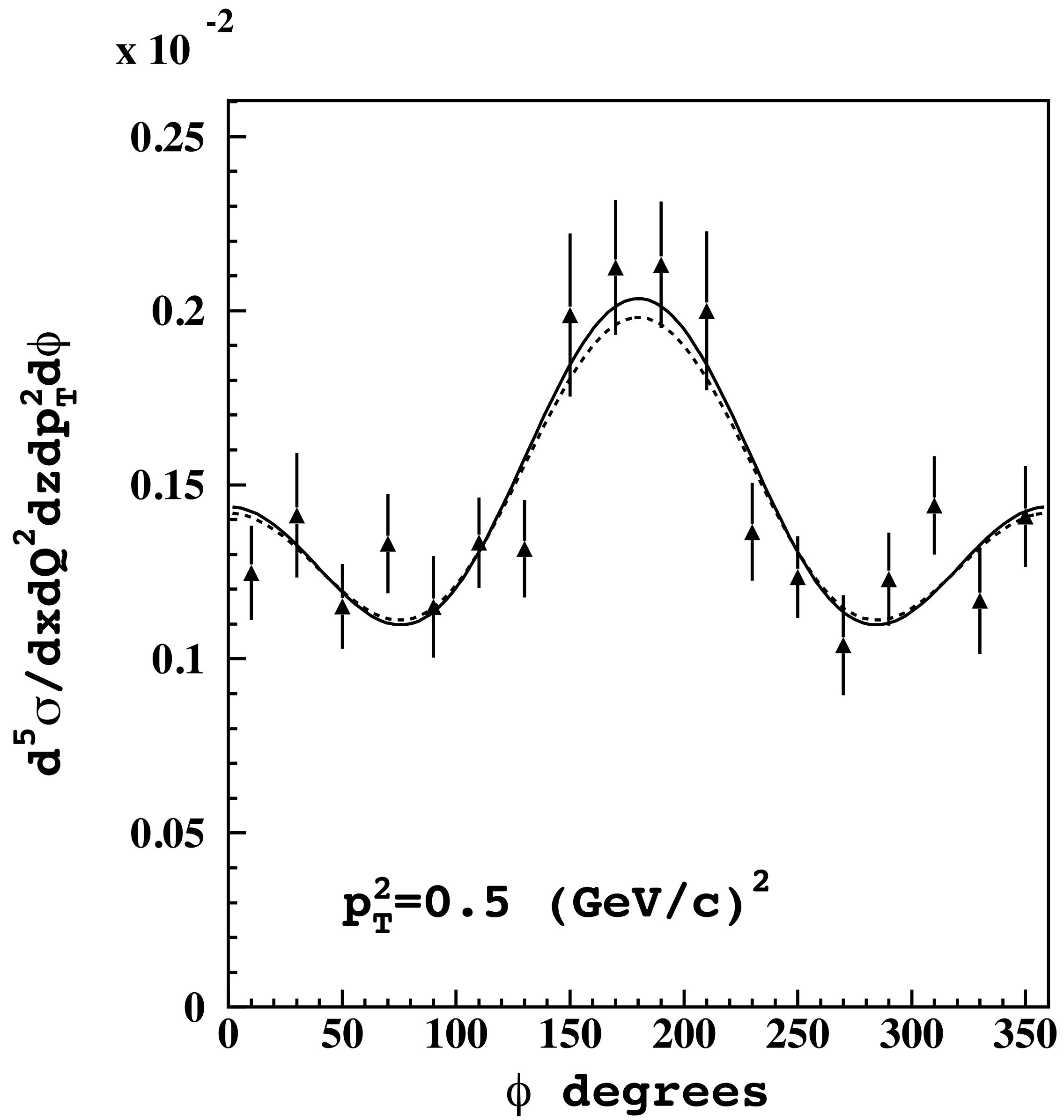
EMC data, μp and μd, *E* between 100 and 280 GeV

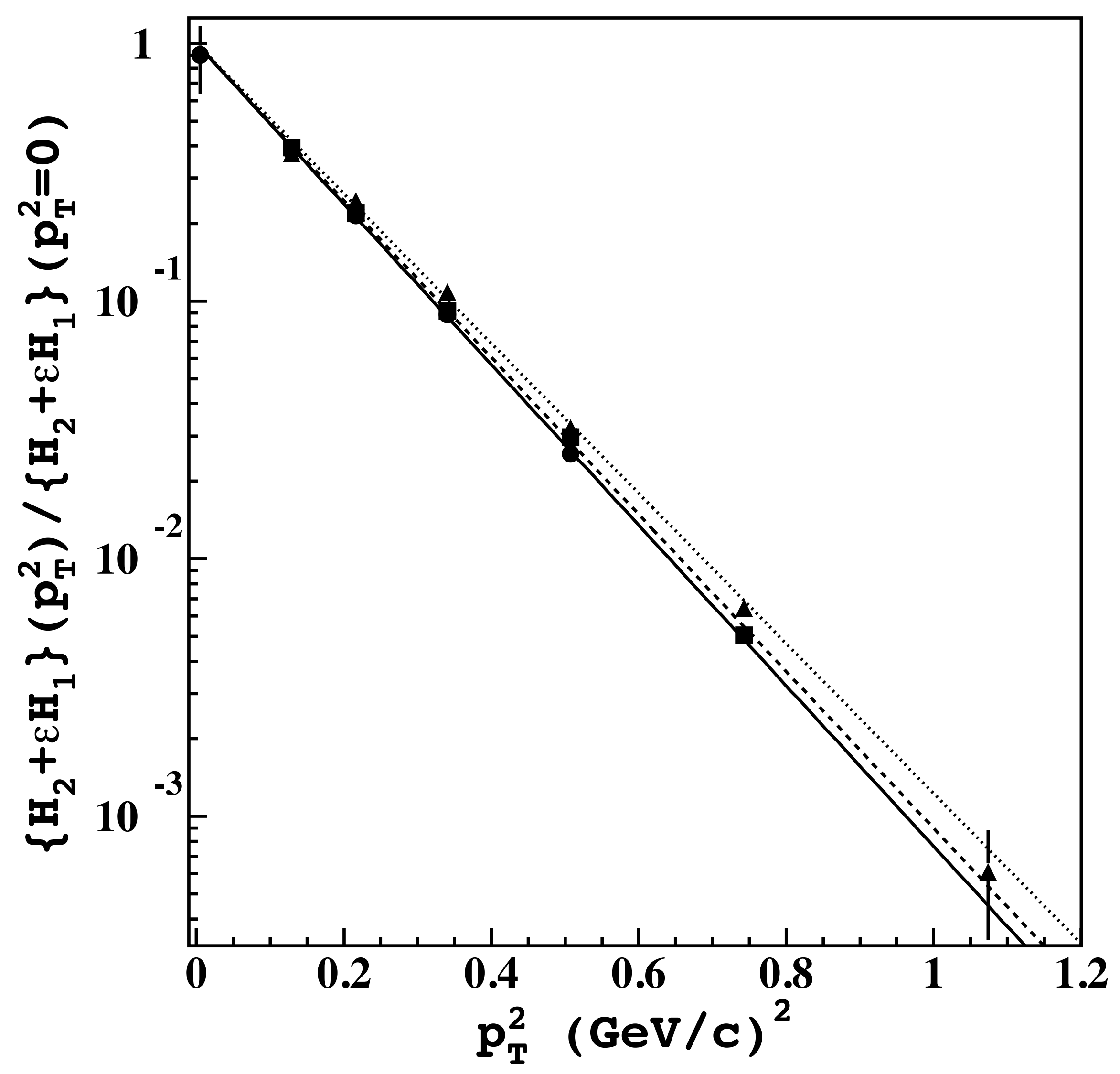
$$\langle k_\perp^2 \rangle = 0.28\ (\mathrm{GeV})^2 \qquad \langle p_\perp^2 \rangle = 0.25\ (\mathrm{GeV})^2$$

M.A., M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia and A. Prokudin

CLAS data, arXiv:0809.1153

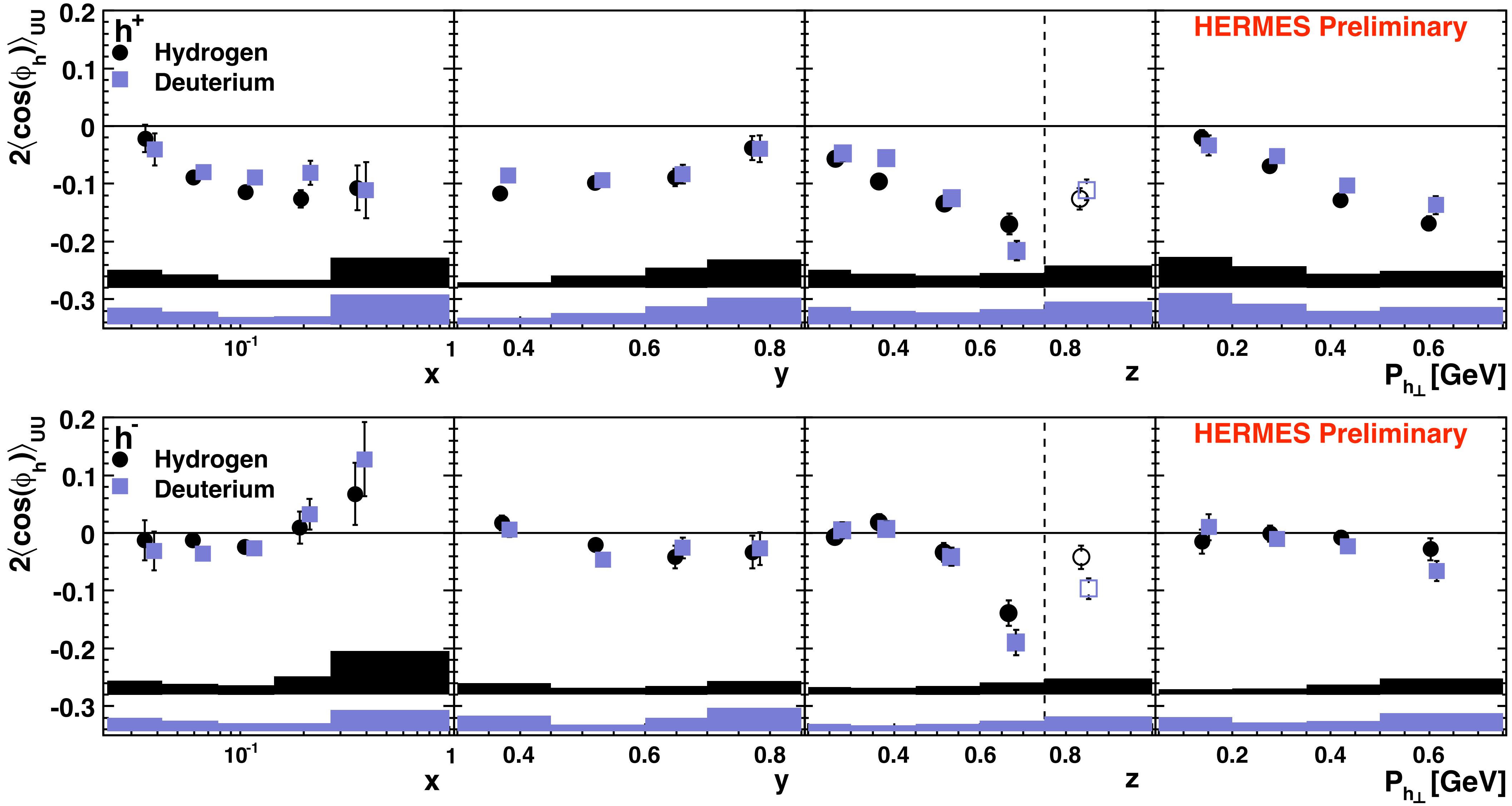
$$\frac{\mathrm{d}^5\sigma}{\mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}z\,\mathrm{d}P_T^2\,\mathrm{d}\phi} = C\left[\epsilon\mathcal{H}_1 + \mathcal{H}_2 + A\cos\phi + B\cos(2\phi)\right]$$





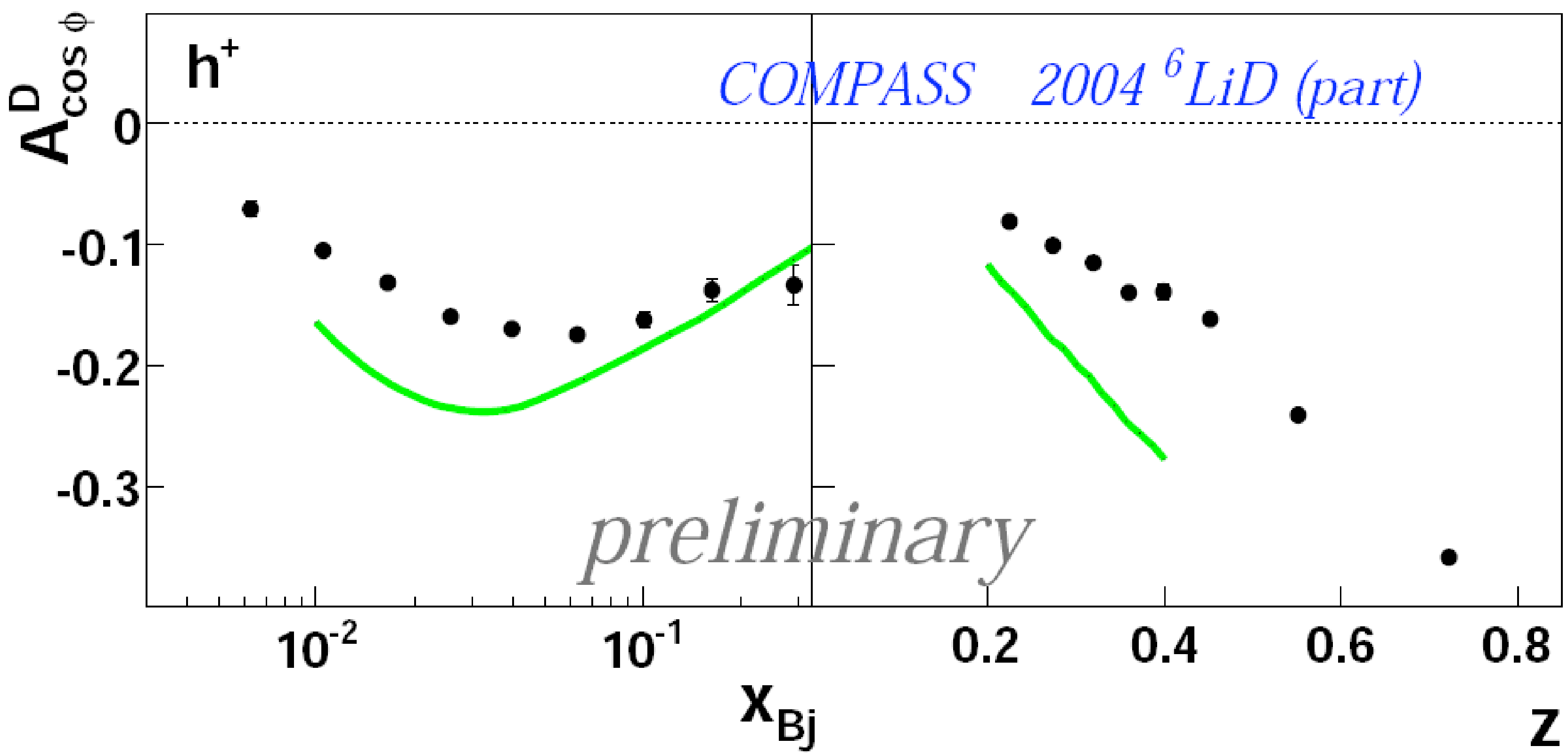
$\cos\phi$ dependence observed by HERMES

F. Giordano and R. Lamb, arXiv:0901.2438 [hep-ex]



and by COMPASS

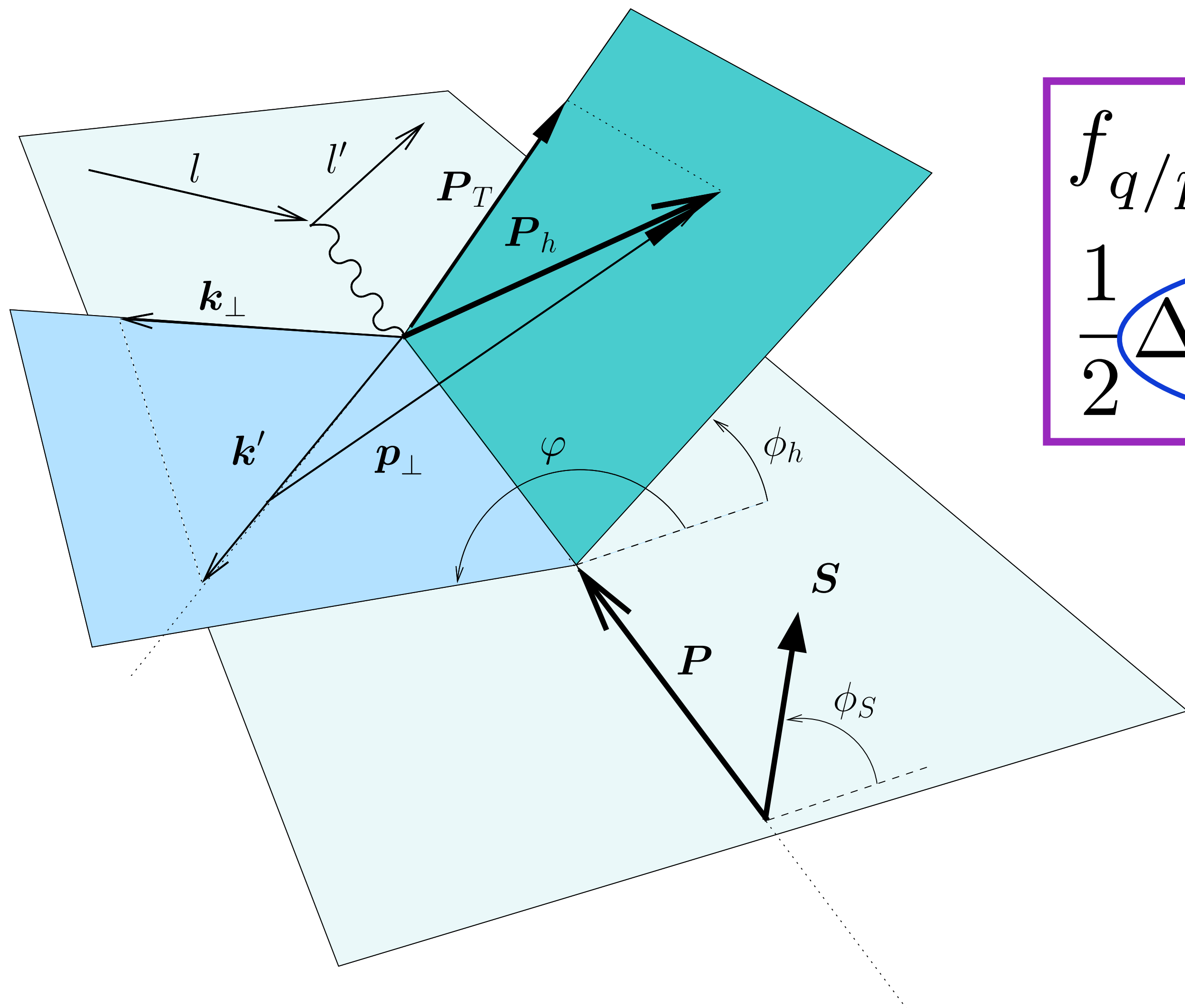
W. Käfer, on behalf of the COMPASS collaboration, talk at Transversity 2008, Ferrara



errors shown are statistical only

comparison with:

M. Anselmino, M. Boglione, A. Prokudin, C. Türk
Eur. Phys. J. A 31, 373-381 (2007)
does not include Boer – Mulders contribution



$$f_{q/p,\boldsymbol{S}}(x,\boldsymbol{k}_\perp) = f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x,k_\perp)\,\boldsymbol{S}\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

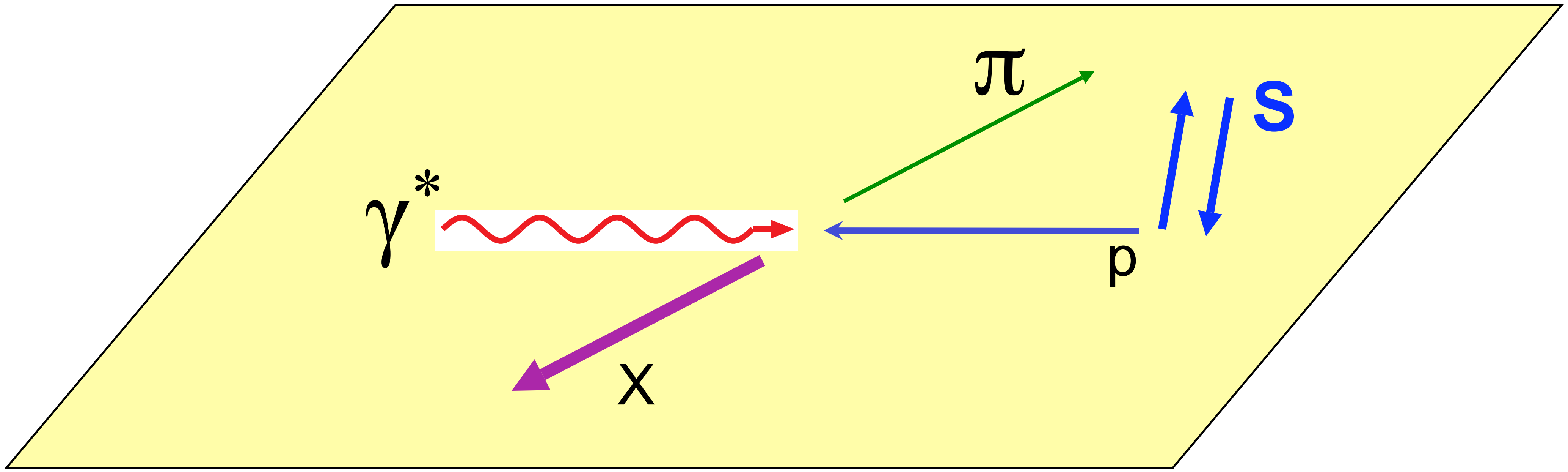
$$\boldsymbol{p}_\perp = \boldsymbol{P}_T - z\,\boldsymbol{k}_\perp$$

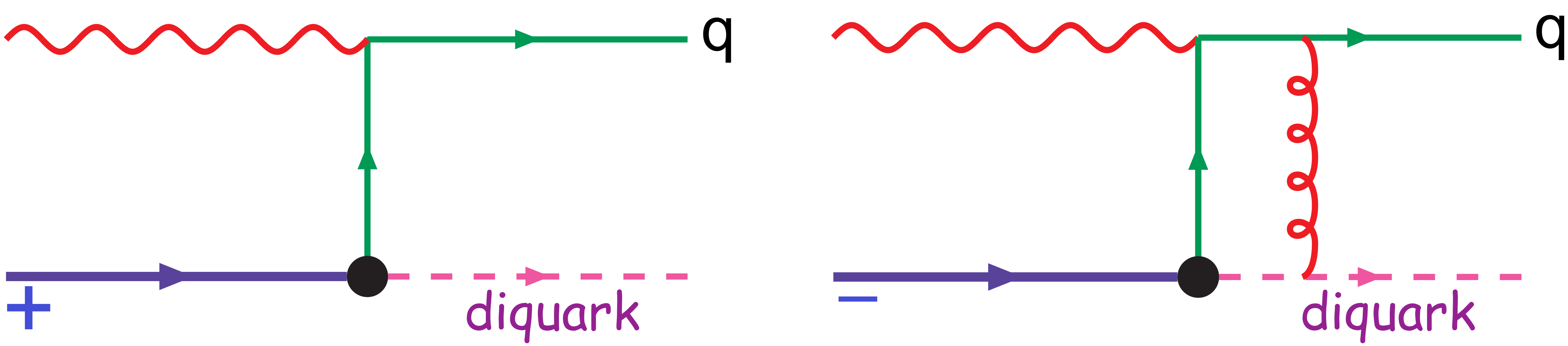
Sivers asymmetry

$$A_{UT}^{\sin(\Phi_h-\Phi_S)} \equiv 2\,\frac{\int d\Phi_S\,d\Phi_h\,[d\sigma^\uparrow - d\sigma^\downarrow]\,\sin(\Phi_h-\Phi_S)}{\int d\Phi_S\,d\Phi_h\,[d\sigma^\uparrow + d\sigma^\downarrow]}$$

$$\frac{\sum_q \int d\Phi_S\,d\Phi_h\,d^2\boldsymbol{k}_\perp\,\Delta^N f_{q/p^\uparrow}(x,k_\perp)\,\sin(\varphi-\Phi_S)\,\frac{d\hat{\sigma}^{\ell q\to\ell q}}{dQ^2}\,D_{h/q}(z,p_\perp)\sin(\Phi_h-\Phi_S)}{\sum_q \int d\Phi_S\,d\Phi_h\,d^2\boldsymbol{k}_\perp\,f_{q/p}(x,k_\perp)\,\frac{d\hat{\sigma}^{\ell q\to\ell q}}{dQ^2}\,D_{h/q}(z,p_\perp)}$$

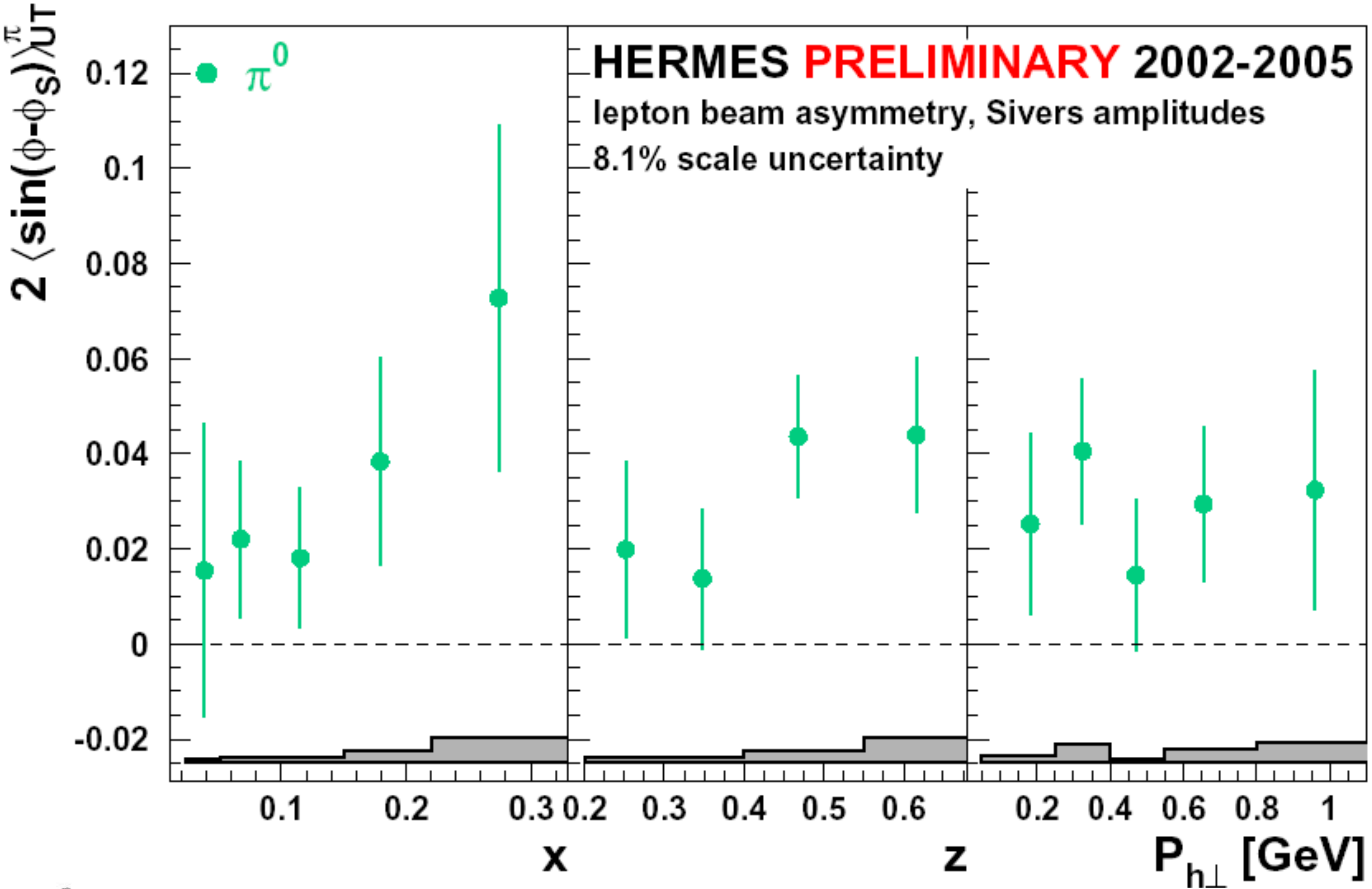
Brodsky, Hwang, Schmidt model for Sivers function

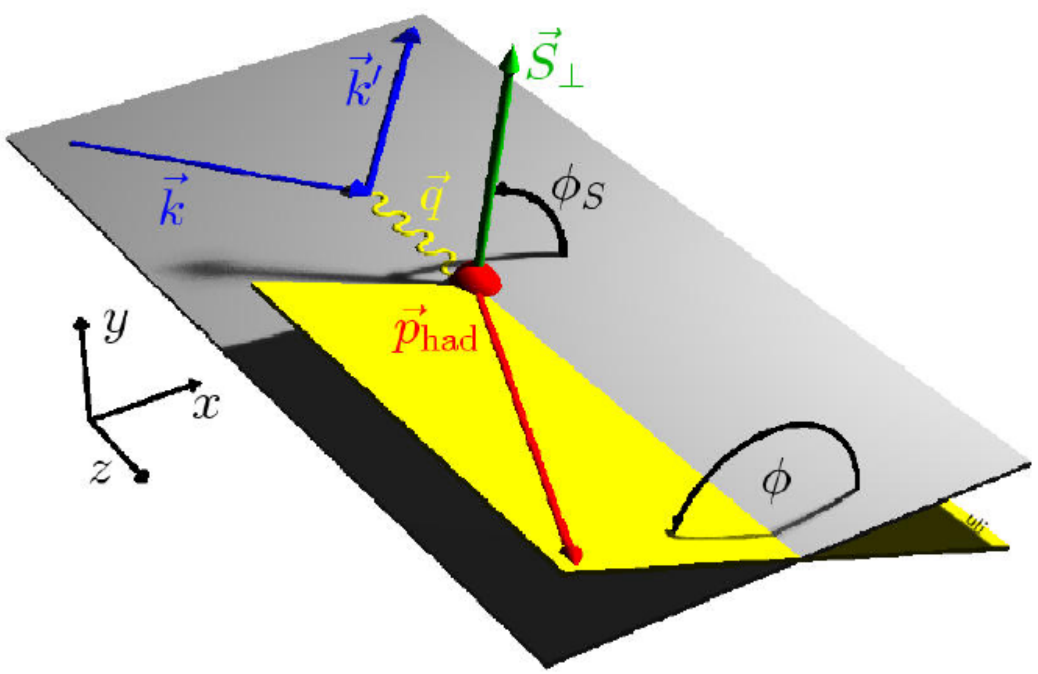




$$A_N \propto \boldsymbol{S} \cdot (\boldsymbol{p} \times \boldsymbol{P}_T) \propto P_T \sin(\phi_\pi - \phi_S)$$

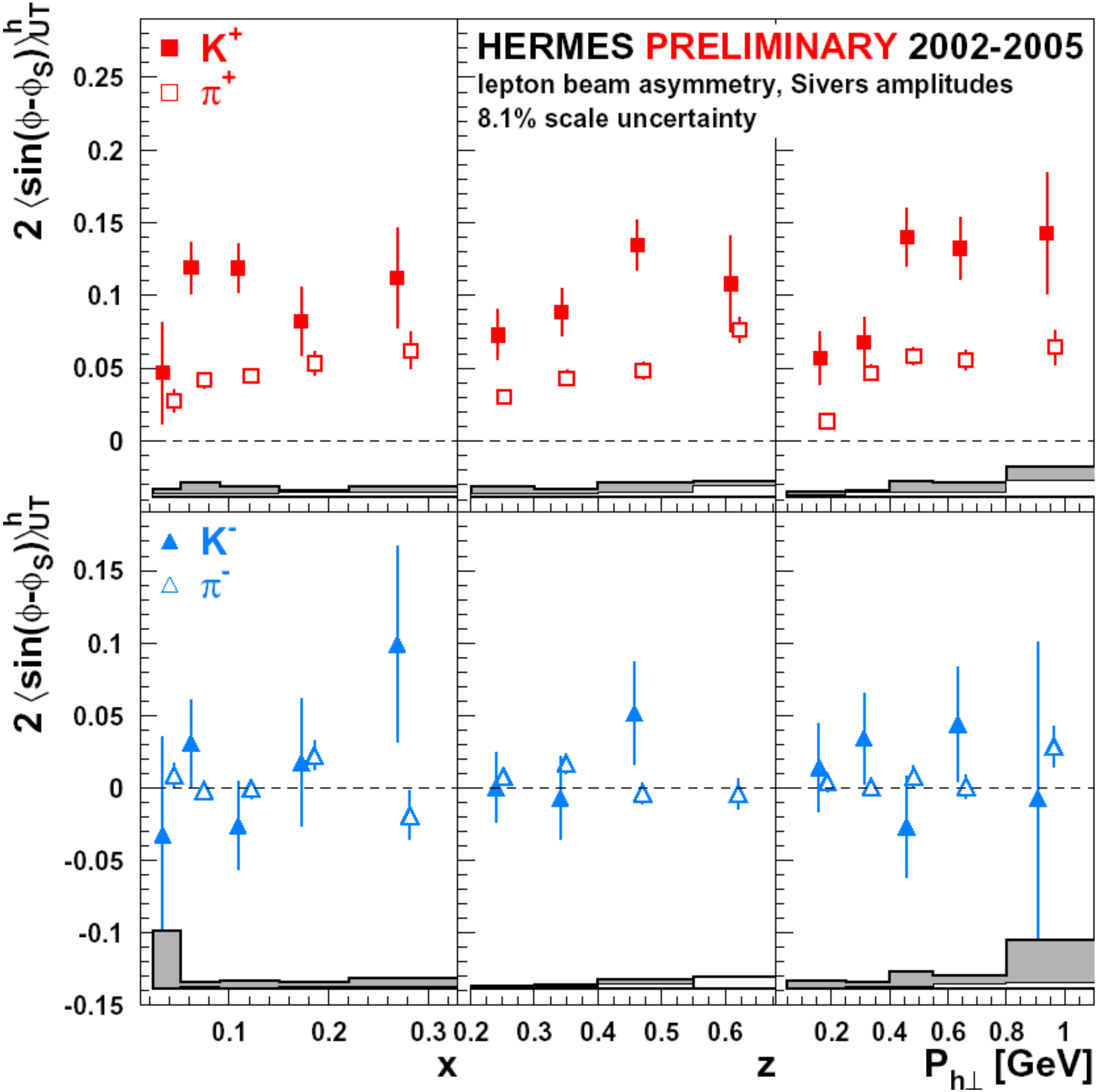
needs $\mathbf{k}_\perp$ dependent quark distribution in $p^\uparrow$ and final state interactions





$$2\langle\sin(\phi-\phi_S)\rangle = A_{UT}^{\sin(\phi-\phi_S)}$$

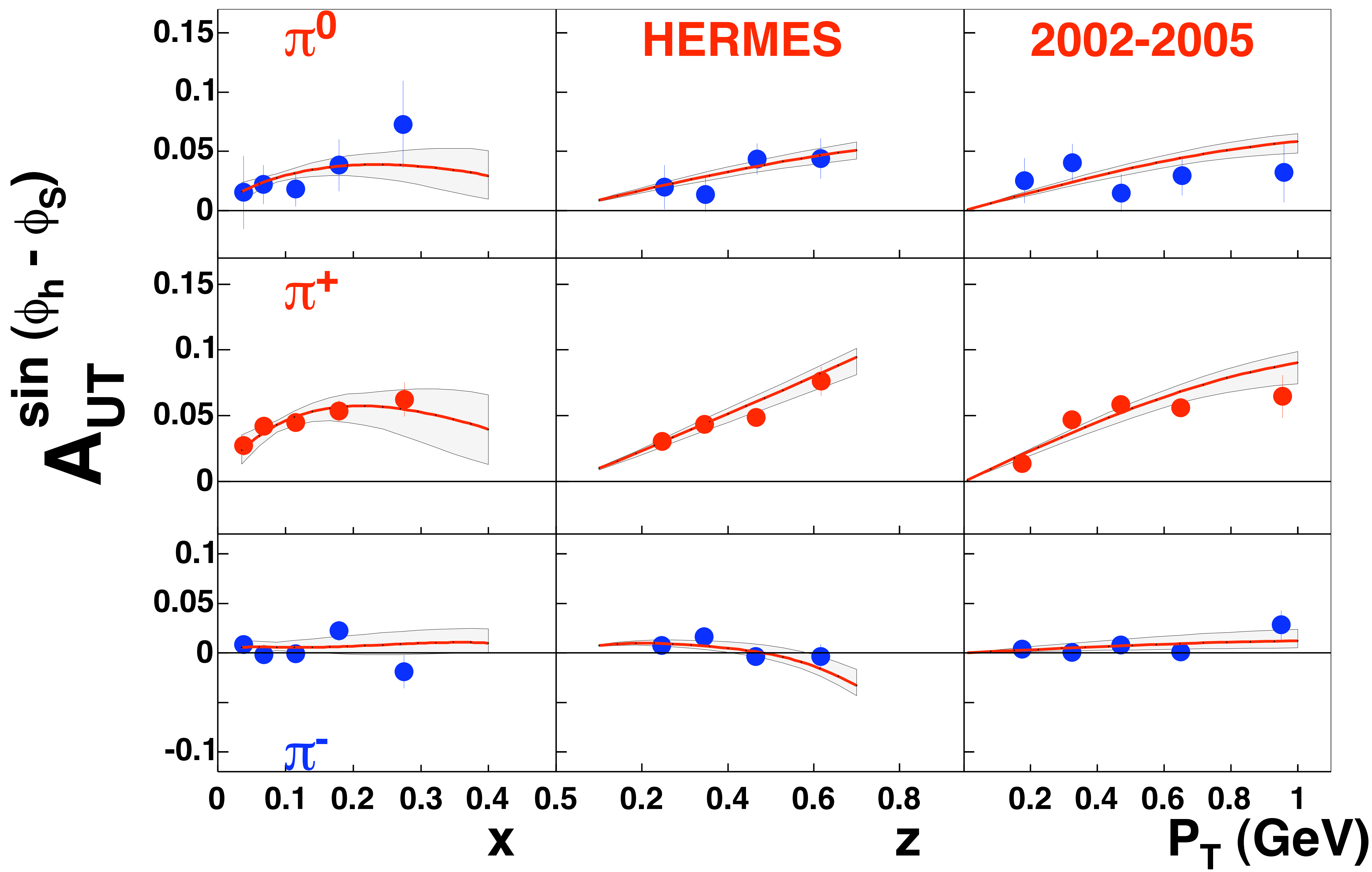
$$\equiv 2\,\frac{\int \mathrm{d}\phi\,\mathrm{d}\phi_S\,[\mathrm{d}\sigma^\uparrow - \mathrm{d}\sigma^\downarrow]\,\sin(\phi-\phi_S)}{\int \mathrm{d}\Phi_h\,\mathrm{d}\Phi_S\,[\mathrm{d}\sigma^\uparrow + \mathrm{d}\sigma^\downarrow]}$$

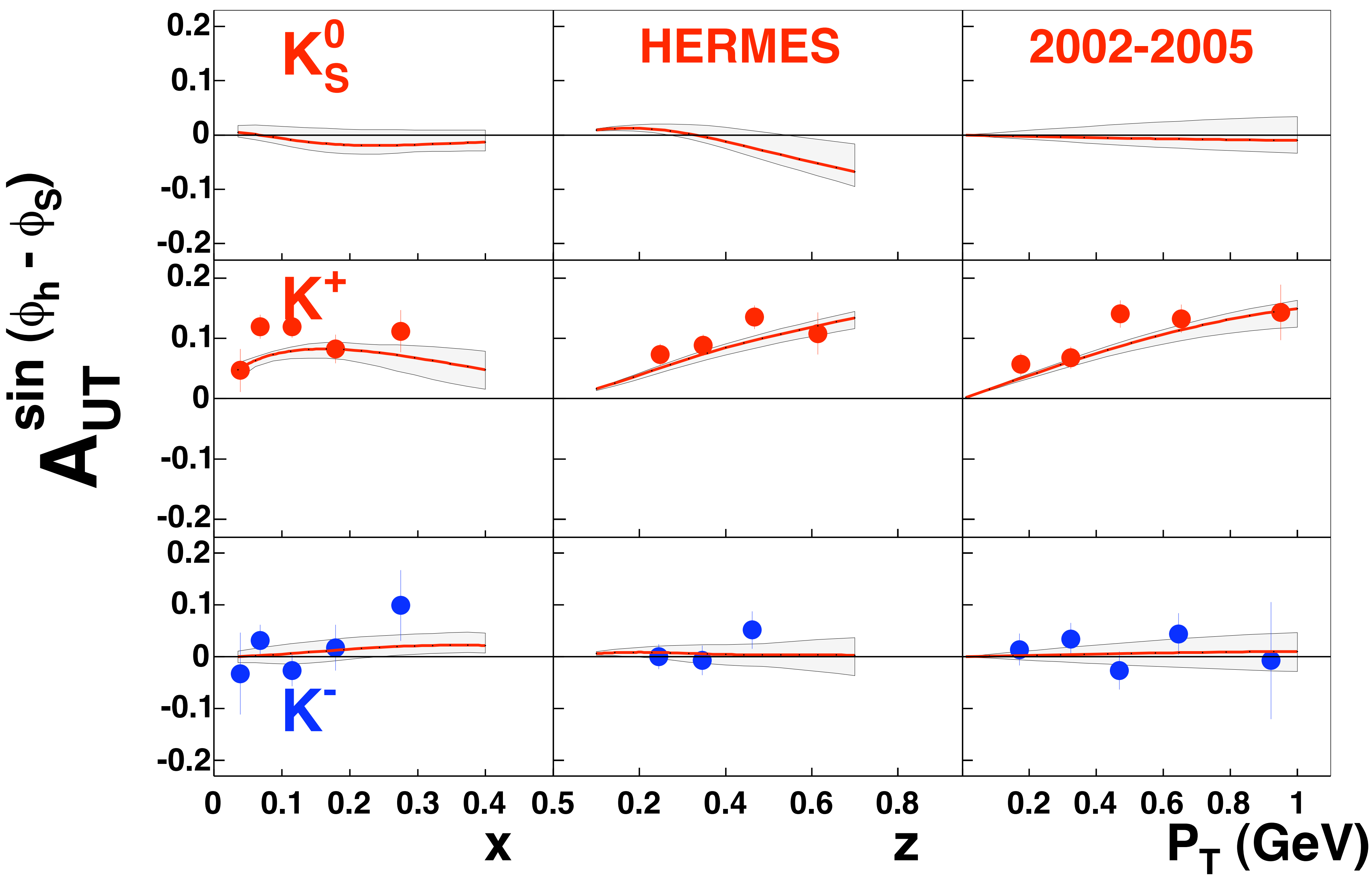


large K^+ asymmetry

Sivers asymmetry best fits

M.A., M. Boglione, U. D'Alesio, A. Kotzinian, S. Melis, F. Murgia, A. Prokudin, C. Turk,
Eur. Phys. J. A39 (2009) 89

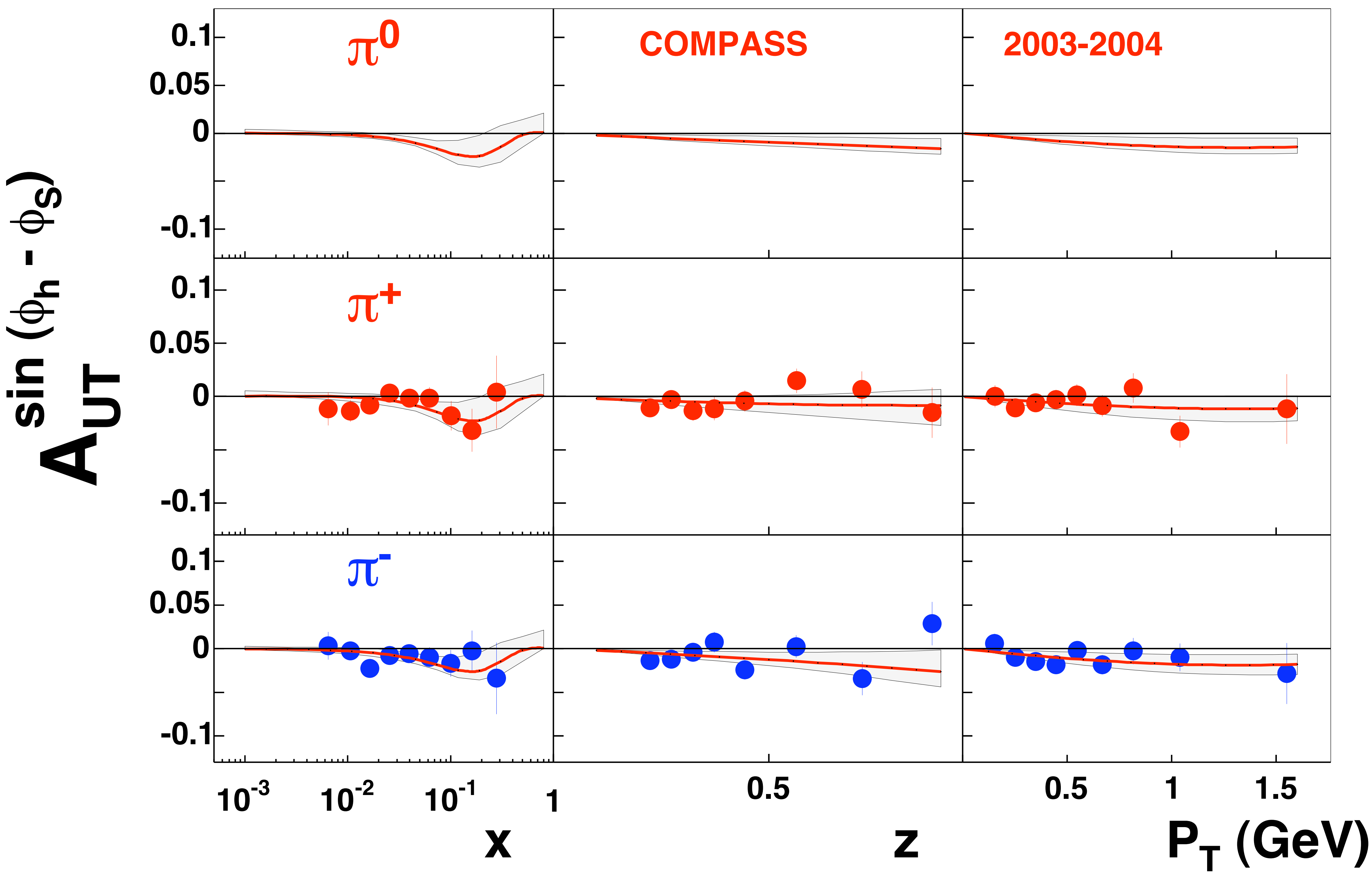




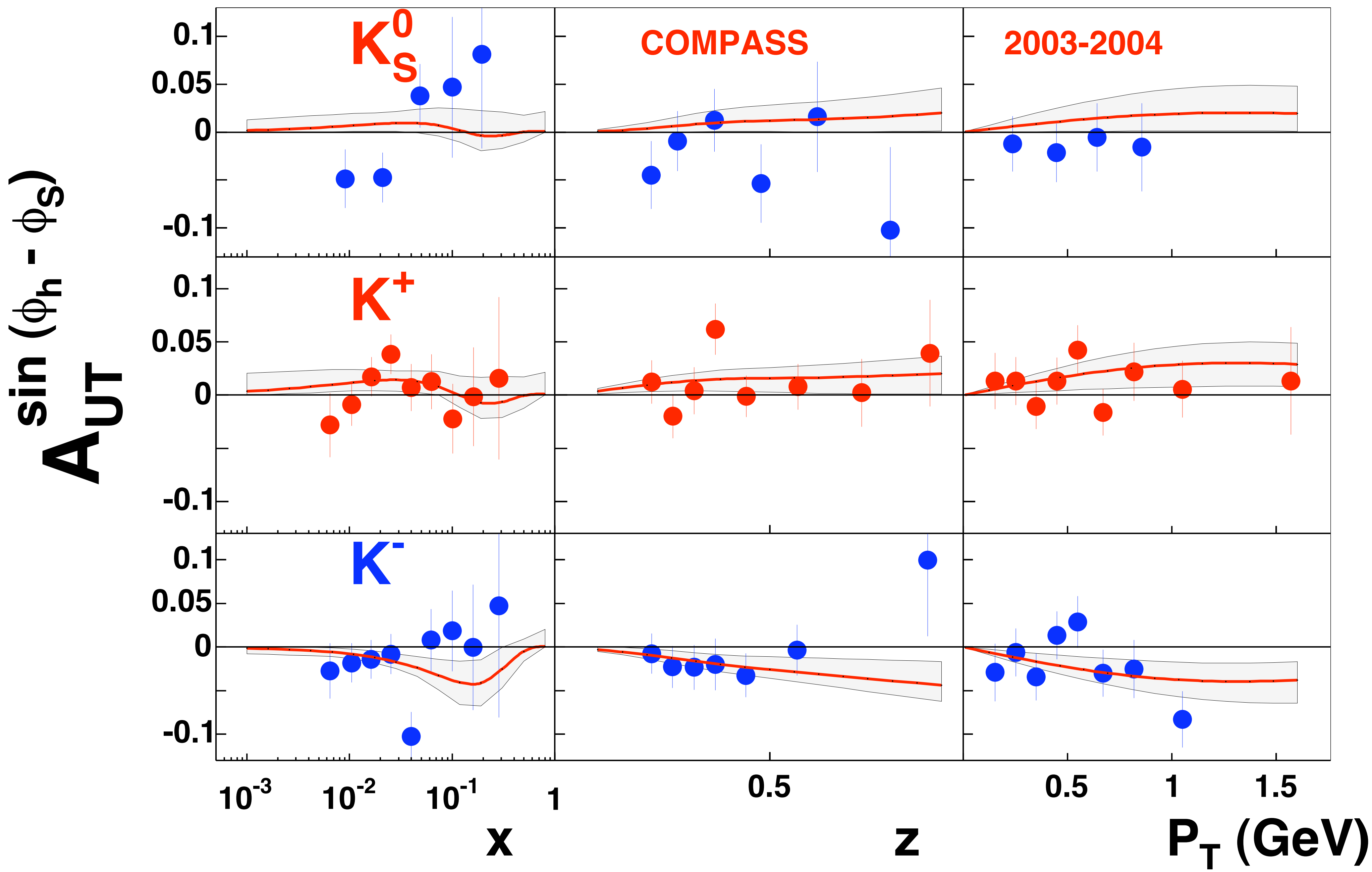
DSS fragmentation functions

$$D_d^{K_S^0} = D_{\bar{d}}^{K_S^0} = \frac{1}{2}\left[D_u^{K^+} + D_{sea}^{K^+}\right]$$

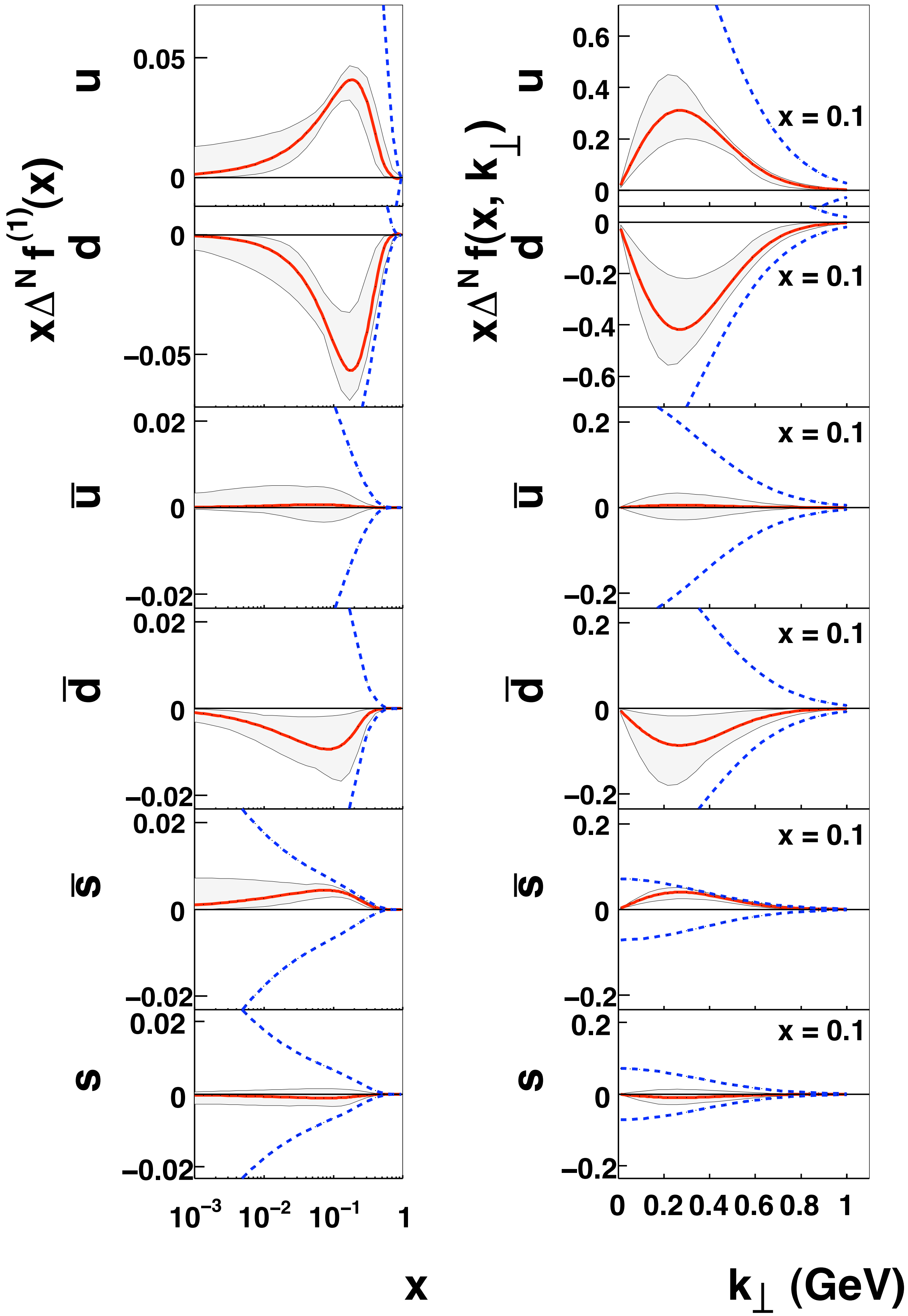
Fit of COMPASS data on deuteron target



$$A_{UT}^{\sin(\Phi_h - \Phi_S)} \propto \underbrace{(\Delta^N f_{u/p^\uparrow} + \Delta^N f_{d/p^\uparrow})}_{\text{cancellation}}(4D_{h/u} + D_{h/d})$$



K_S^0 not included in the fit: computed



extracted Sivers functions

(HERMES and COMPASS deuteron data)

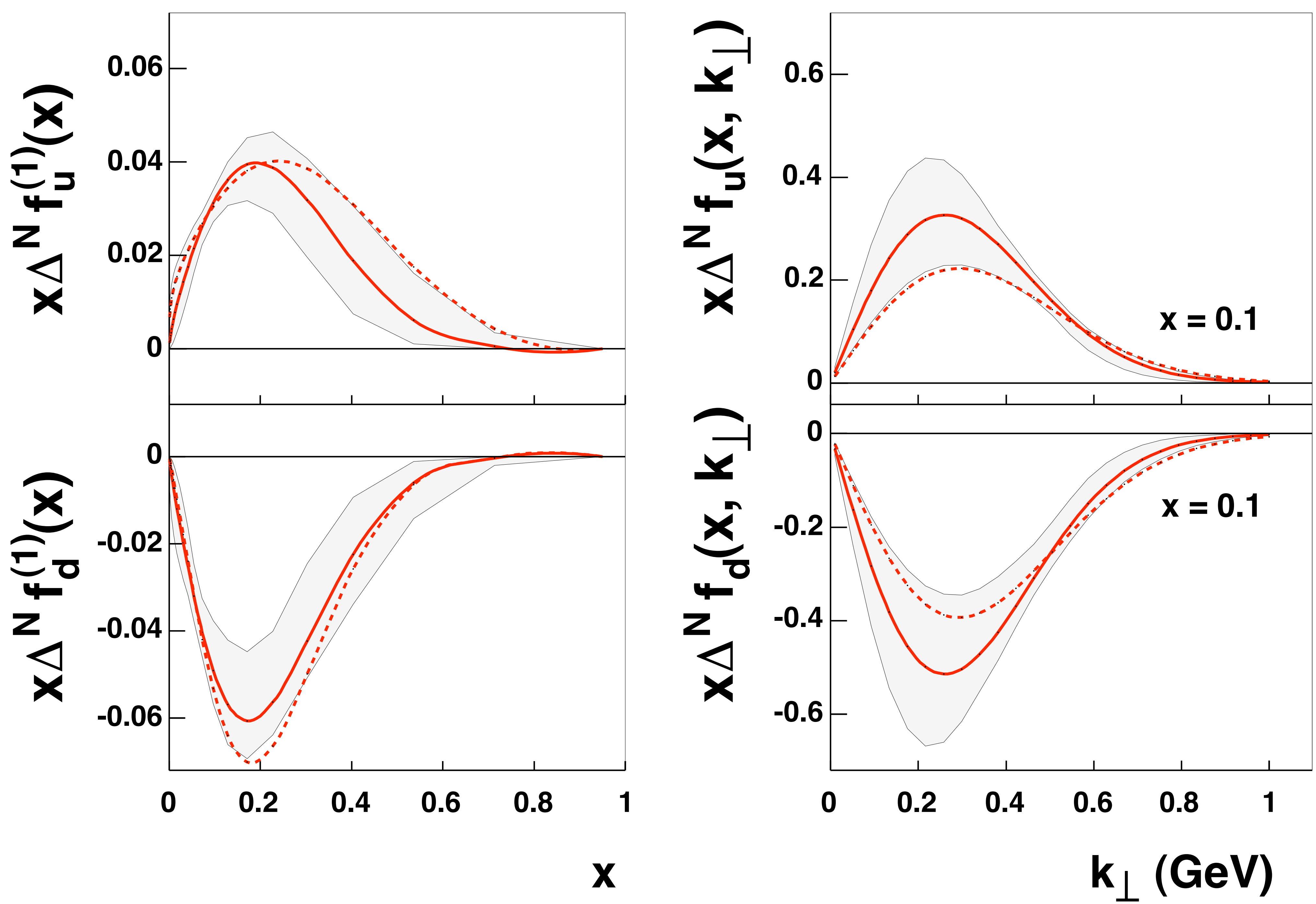
$$\Delta^N f_{u/p^\uparrow} > 0$$

$$\Delta^N f_{d/p^\uparrow} < 0$$

$$\Delta^N f_{\bar{s}/p^\uparrow} > 0$$

$$\Delta^N f^{(1)}_{q/p^\uparrow}(x) \equiv \int d^2\,\boldsymbol{k}_\perp \frac{k_\perp}{4m_p} \Delta^N f_{q/p^\uparrow}(x, k_\perp) = -f_{1T}^{\perp(1)q}(x)$$

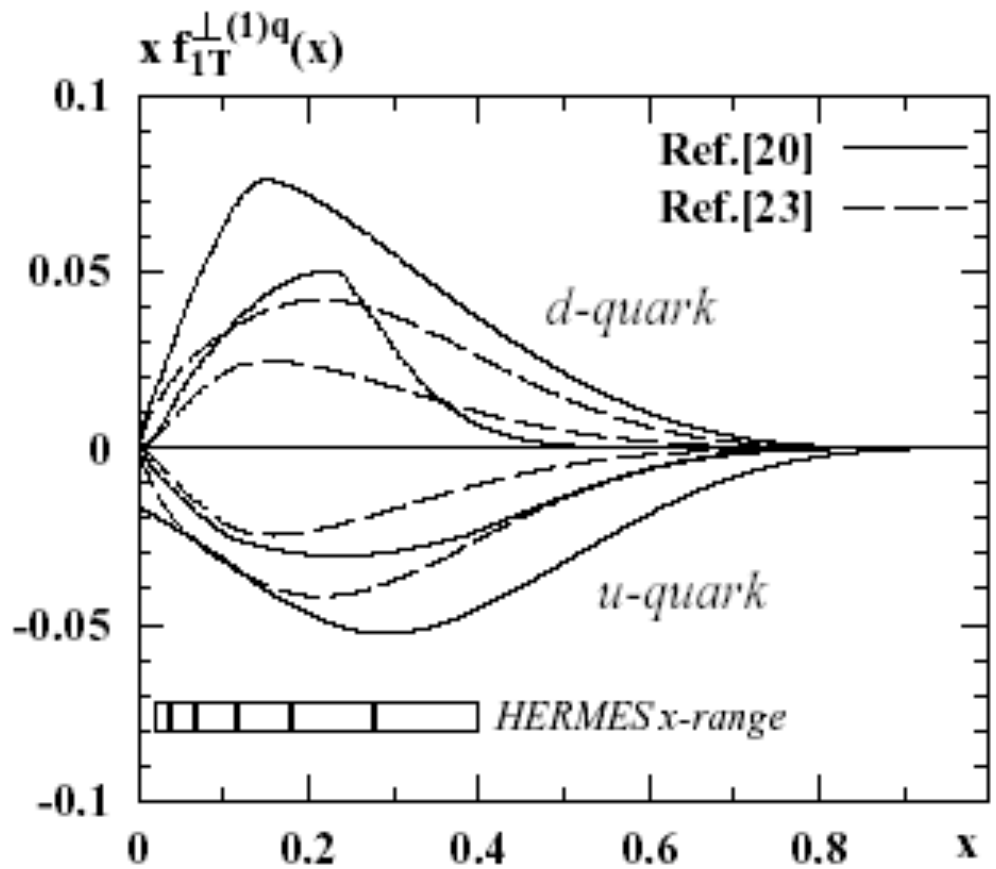
u and d Sivers functions rather well determined

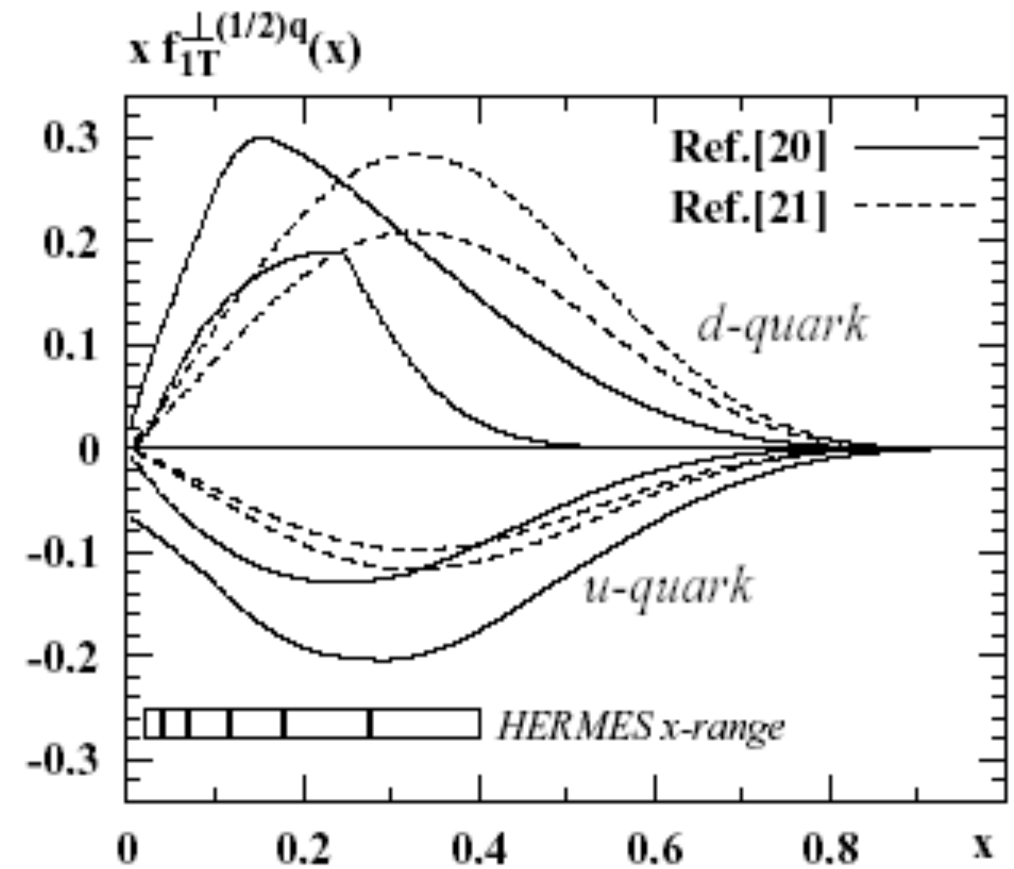


M.A., M. Boglione, U. D'Alesio, A. Kotzinian, S. Melis,
F. Murgia, A. Prokudin, C. Türk

agreement between different groups

M. Anselmino, M. Boglione, J.C. Collins, U. D'Alesio, A.V. Efremov, K. Goeke, A. Kotzinian, S. Menze, A. Metz, F. Murgia, A. Prokudin, P. Schweitzer, W. Vogelsang, F. Yuan

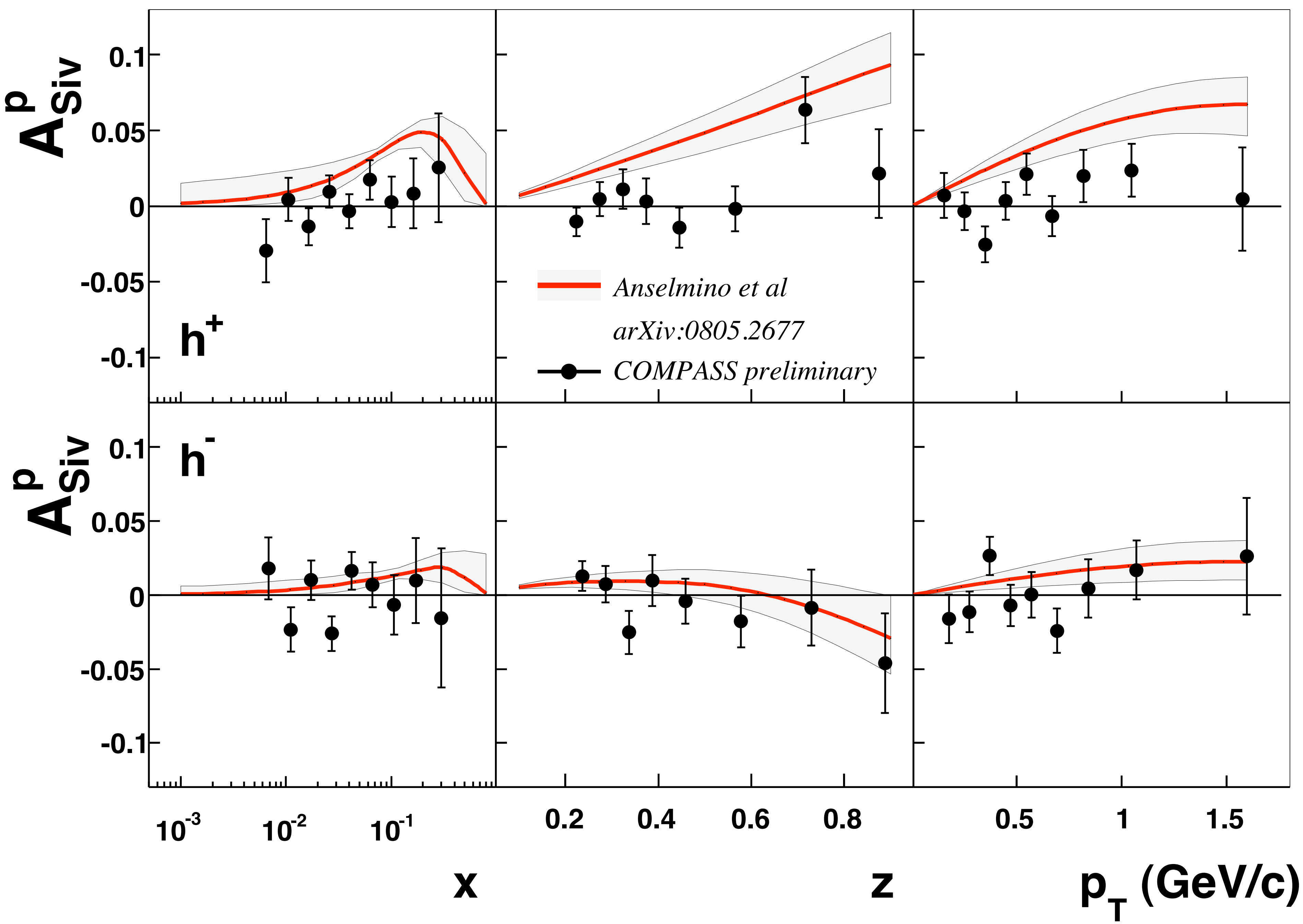




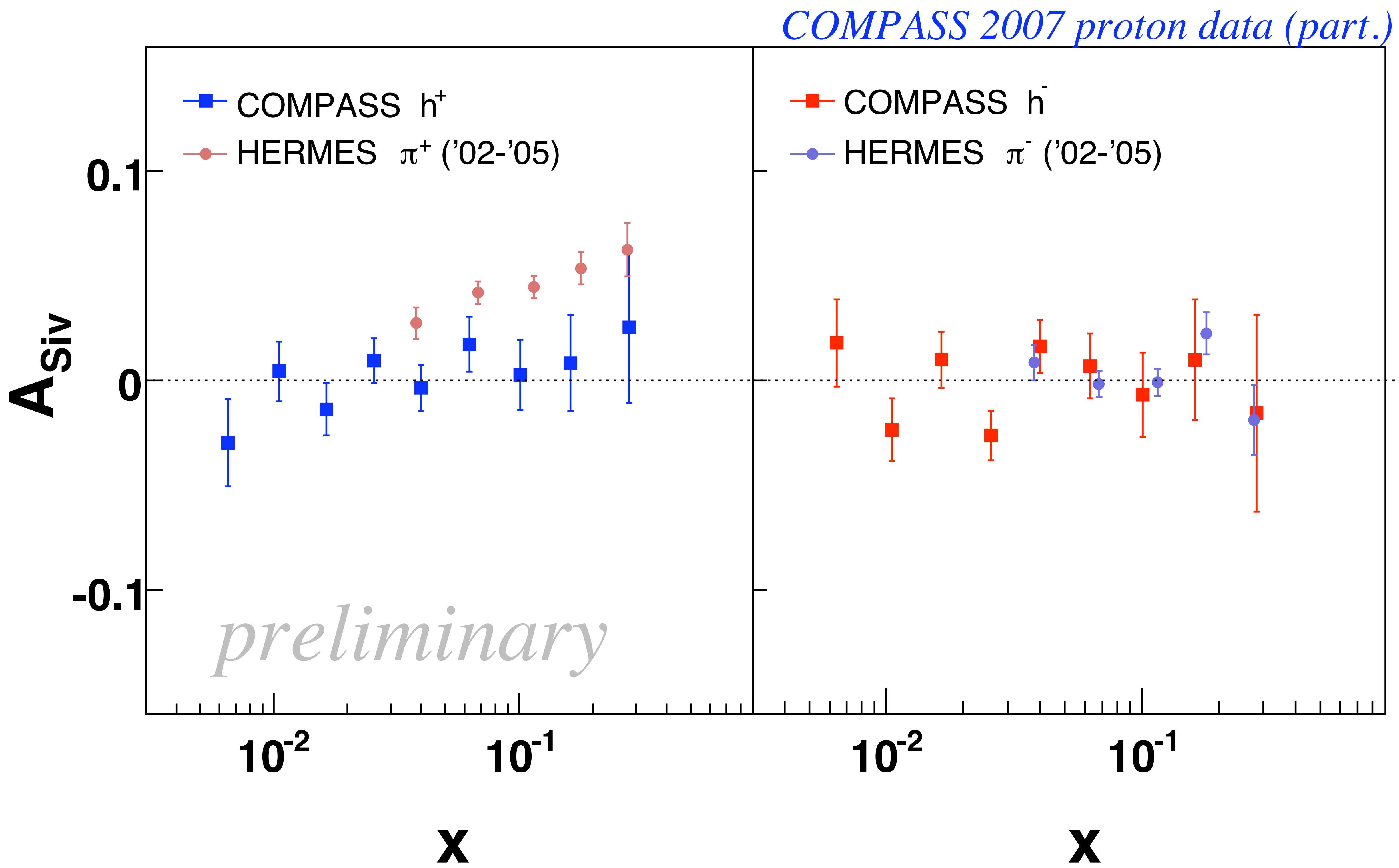
The first and 1/2-transverse moments of the Sivers quark distribution functions. The fits were constrained mainly (or solely) by the preliminary HERMES data in the indicated x-range. The curves indicate the 1-σ regions of the various parameterizations.

$$f_{1T}^{\perp(1)q} = \int d^2\boldsymbol{k}_\perp \frac{k_\perp^2}{2M^2} f_{1T}^{\perp q}(x,k_\perp) \qquad f_{1T}^{\perp(1/2)q}(x) = \int d^2\boldsymbol{k}_\perp \frac{k_\perp}{M} f_{1T}^{\perp q}(x,k_\perp)$$

Predictions for COMPASS, with a proton target, and comparison with data (arXiv:0808.0086

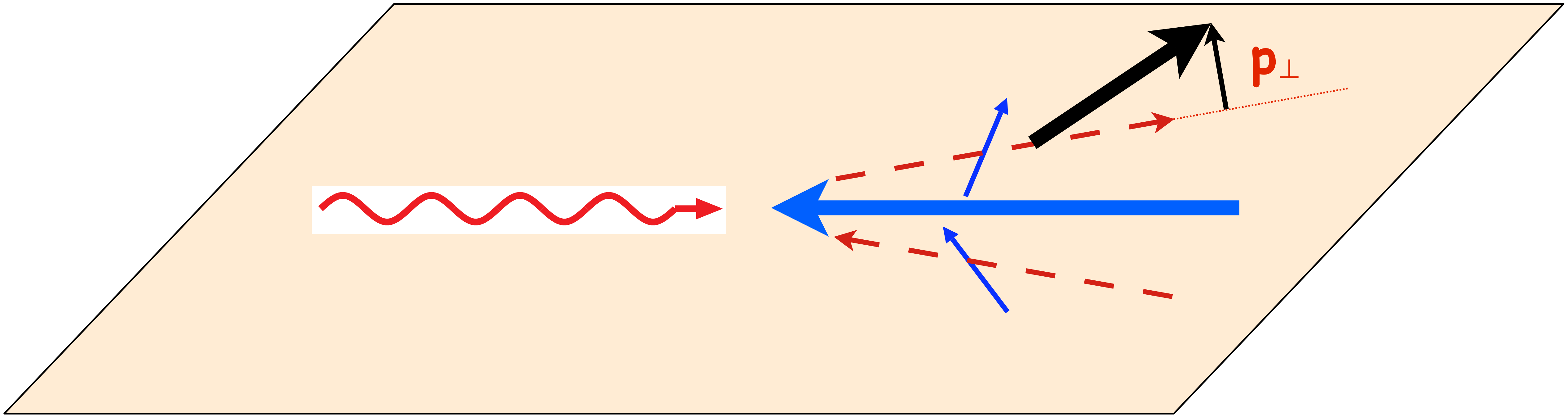


Sivers asymmetry: COMPASS vs HERMES, problems?



courtesy of F. Bradamante

Collins effect



$$
\begin{aligned}
D_{h/q,\boldsymbol{s}_q}(z,\boldsymbol{p}_\perp) &= D_{h/q}(z,p_\perp) + \frac{1}{2}\,\Delta^N D_{h/q^\uparrow}(z,p_\perp)\,\boldsymbol{s}_q \cdot (\hat{\boldsymbol{p}}_q \times \hat{\boldsymbol{p}}_\perp) \\
&= D_{h/q}(z,p_\perp) + \frac{p_\perp}{zM_h}\,H_1^{\perp q}(z,p_\perp)\,\boldsymbol{s}_q \cdot (\hat{\boldsymbol{p}}_q \times \hat{\boldsymbol{p}}_\perp)
\end{aligned}
$$

Collins asymmetry

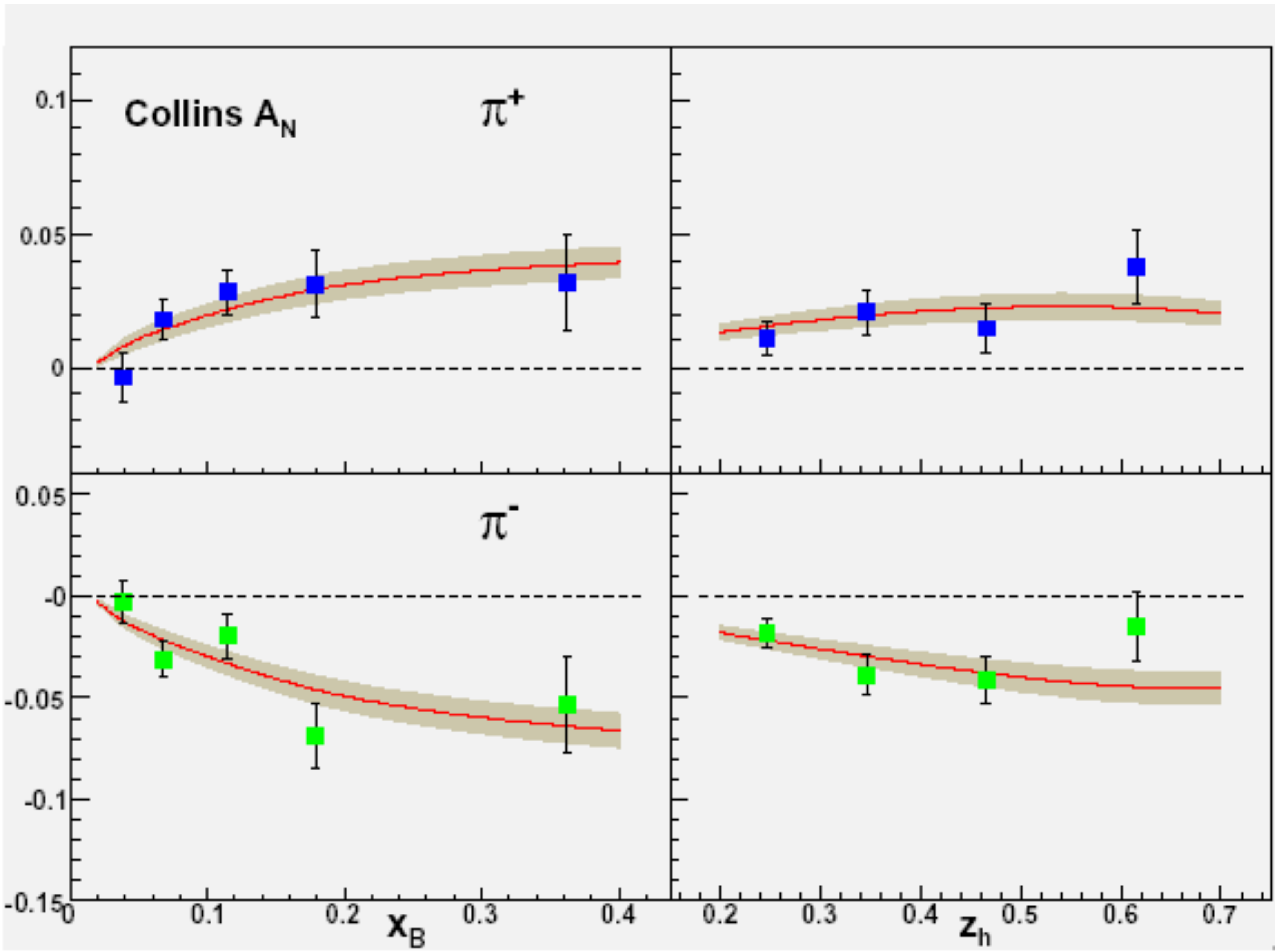
$$A_{UT}^{\sin(\Phi_h+\Phi_S)} \equiv 2\,\frac{\int \mathrm{d}\Phi_h\,\mathrm{d}\Phi_S\,[\mathrm{d}\sigma^{\uparrow}-\mathrm{d}\sigma^{\downarrow}]\,\sin(\Phi_h+\Phi_S)}{\int \mathrm{d}\Phi_h\,\mathrm{d}\Phi_S\,[\mathrm{d}\sigma^{\uparrow}+\mathrm{d}\sigma^{\downarrow}]}$$

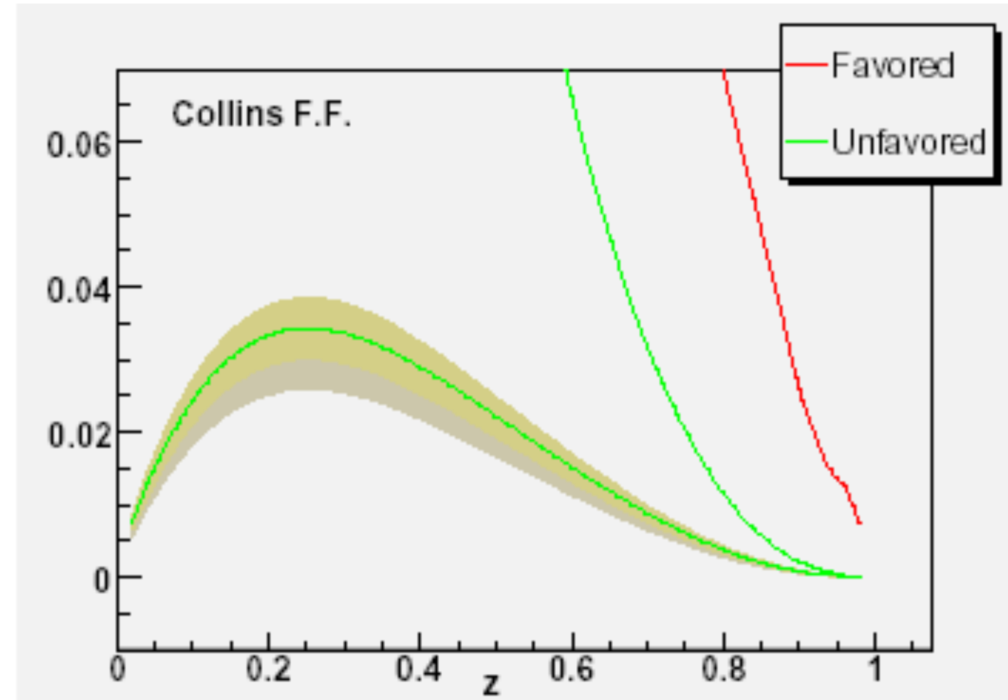
$$A_{UT}^{\sin(\Phi_h+\Phi_S)} = \frac{\sum_q \int d\Phi_S\,d\Phi_h\,d^2\boldsymbol{k}_\perp\, h_{1q}(x,k_\perp)\,\frac{d\Delta\hat{\sigma}^{\ell q\to \ell q}}{dQ^2}\,\Delta^N D_{h/q^\uparrow}(z,\boldsymbol{p}_\perp)\sin(\Phi_h+\Phi_S)}{\sum_q \int d\phi_S\,d\phi_h\,d^2\boldsymbol{k}_\perp\, f_{q/p}(x,k_\perp)\,\frac{d\hat{\sigma}^{\ell q\to \ell q}}{dQ^2}\,D_{h/q}(z,p_\perp)}$$

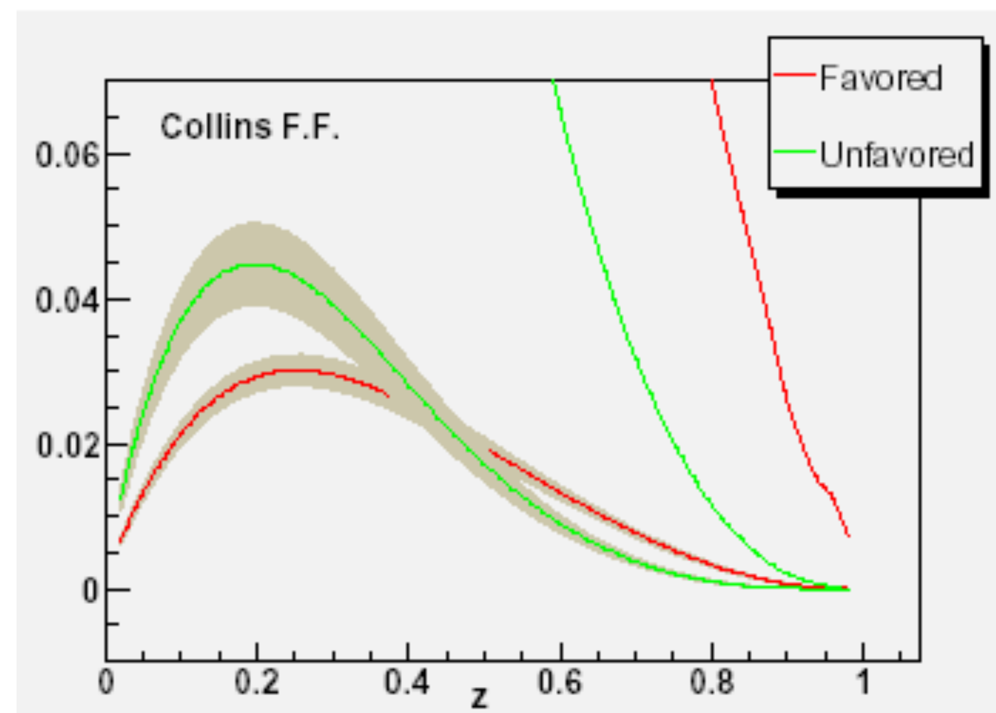
$$\mathrm{d}\Delta\hat{\sigma} = \mathrm{d}\hat{\sigma}^{\ell q^\uparrow\to \ell q^\uparrow} - \mathrm{d}\hat{\sigma}^{\ell q^\uparrow\to \ell q^\downarrow}$$

Collins effect in SIDIS couples to transversity fit to HERMES data on $A_{UT}^{\sin(\Phi_h+\Phi_S)}$

W. Vogelsang and F. Yuan



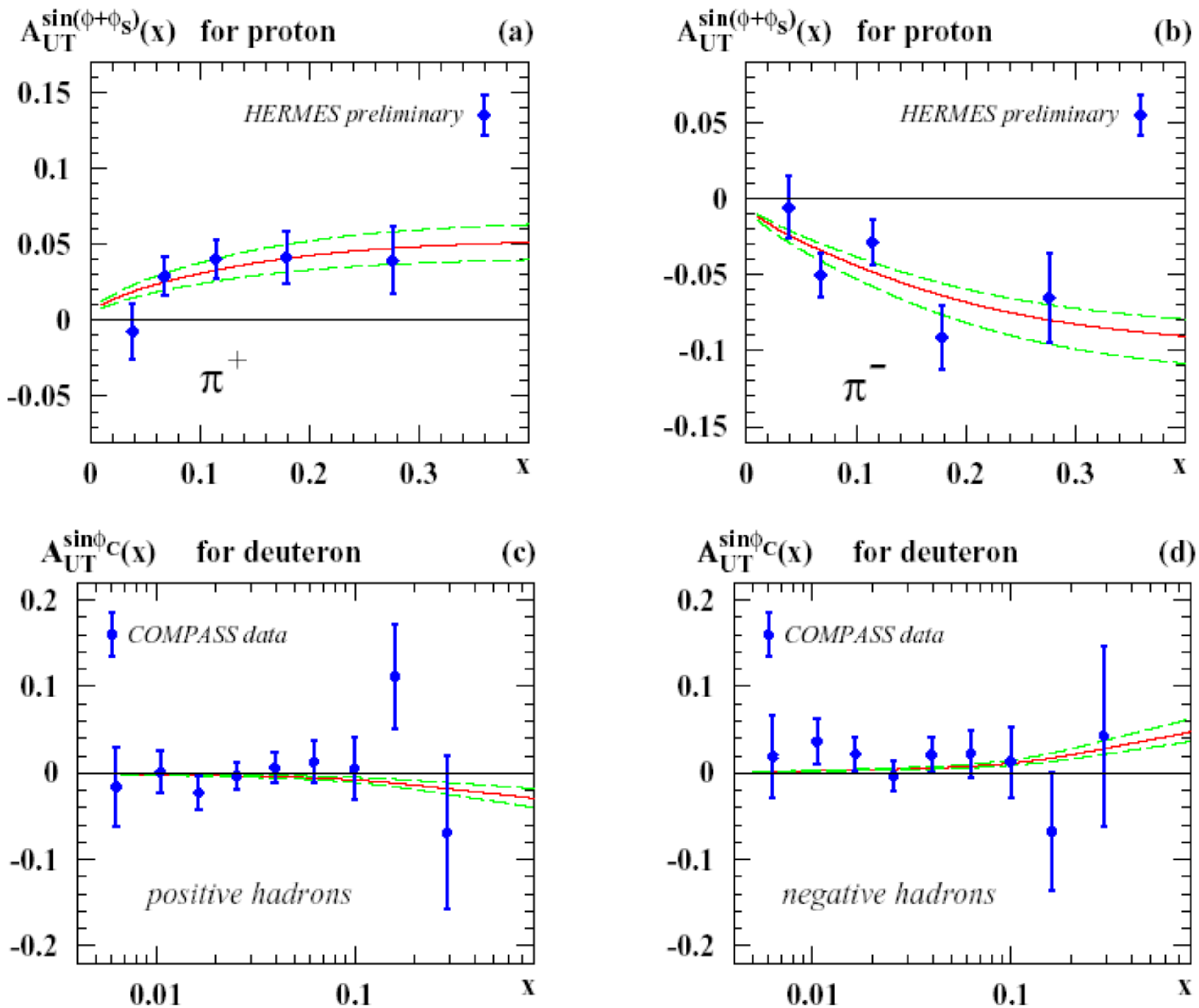




Soffer-saturated h_1 $\left(2\,|\,h_1\,| = \Delta q + q\right)$

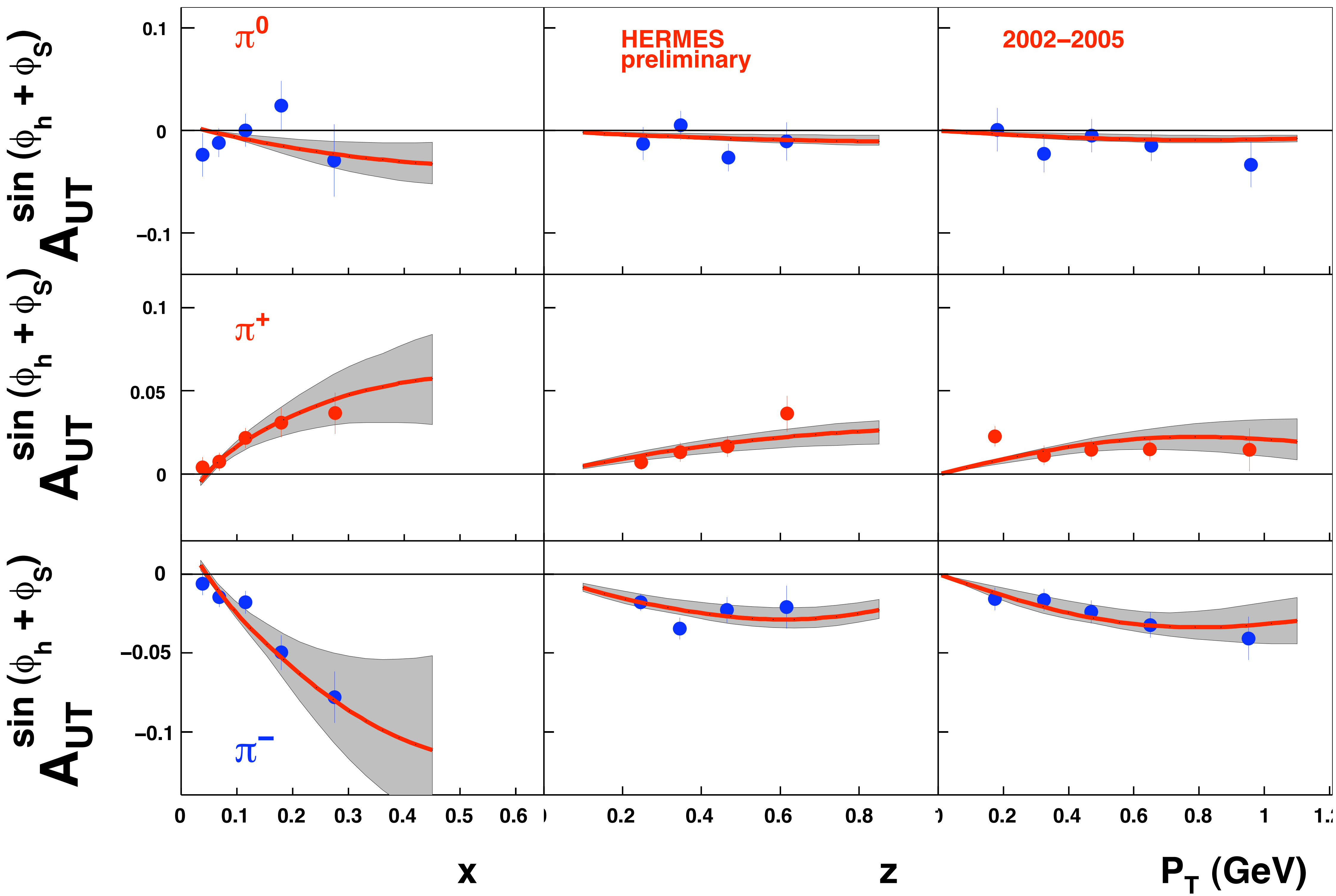
A. V. Efremov, K. Goeke and P. Schweitzer

(h_1 from quark-soliton model)

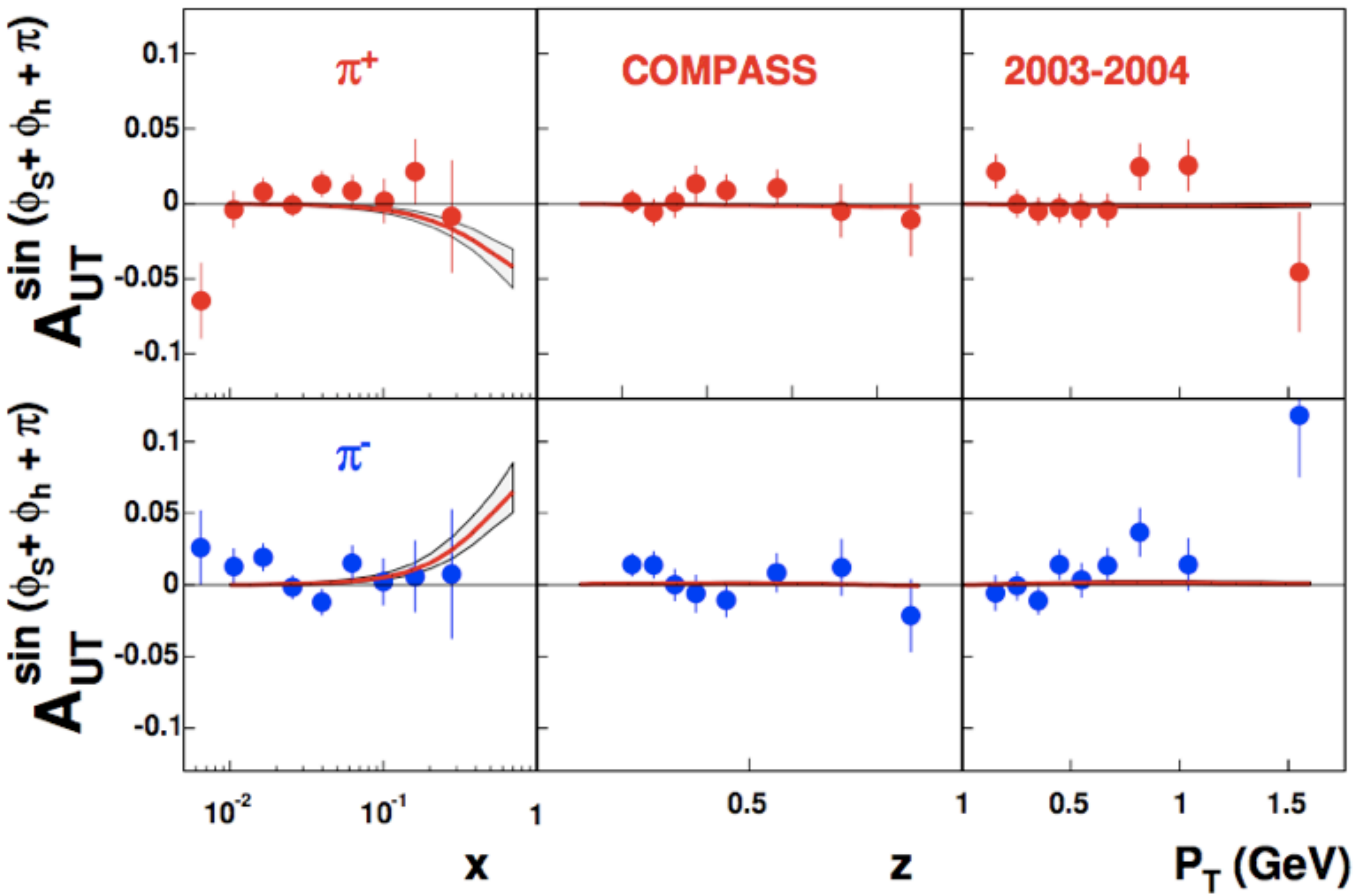


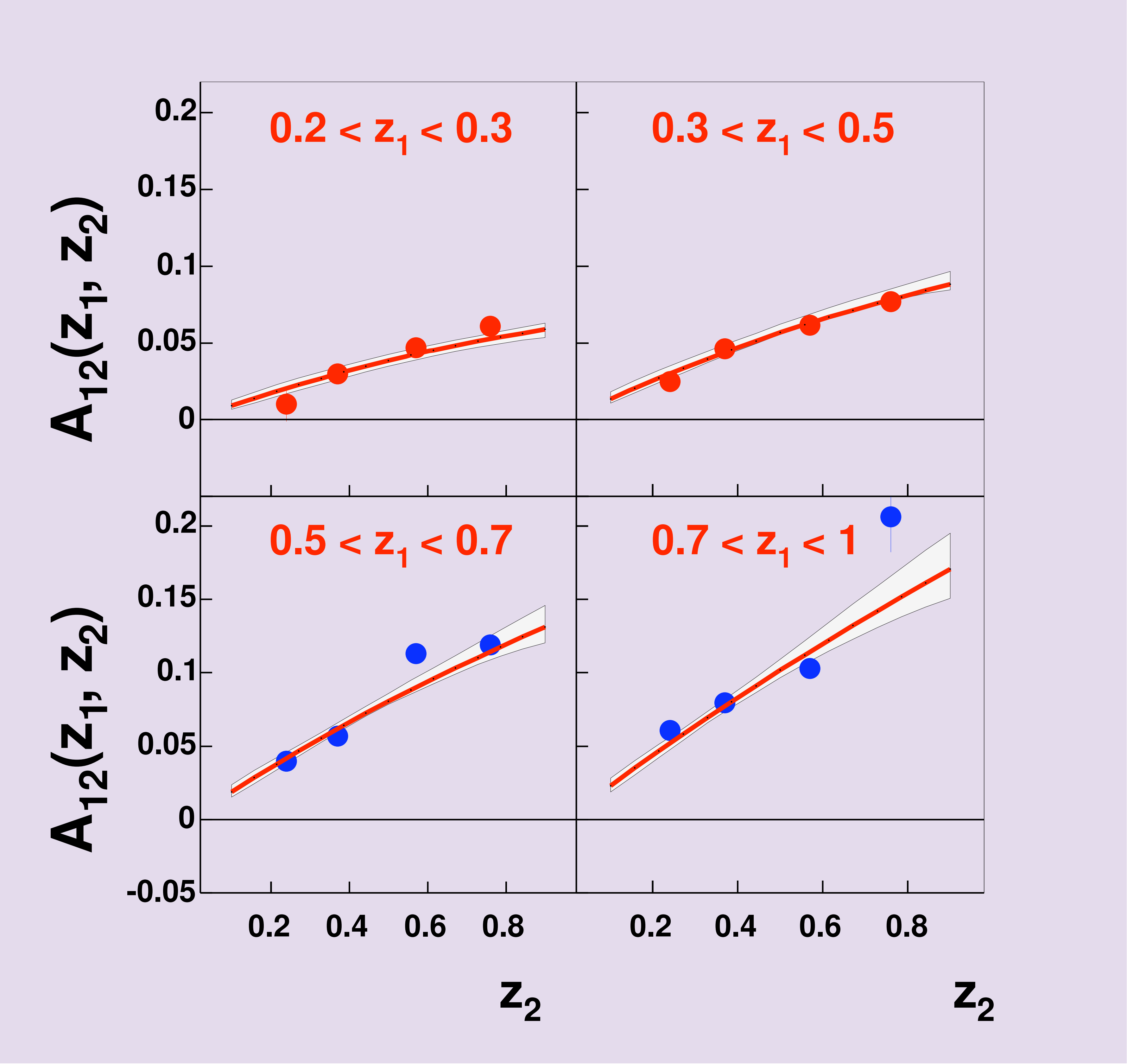
Collins asymmetry best fit

M. A., M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia, A. Prokudin, S. Melis , e-Print: arXiv:0812.4366 [hep-ph]



M. A., M. Boglione, U. D'Alesio, A. Kotzinian, S. Melis, F. Murgia,A. Prokudin and C. Türk

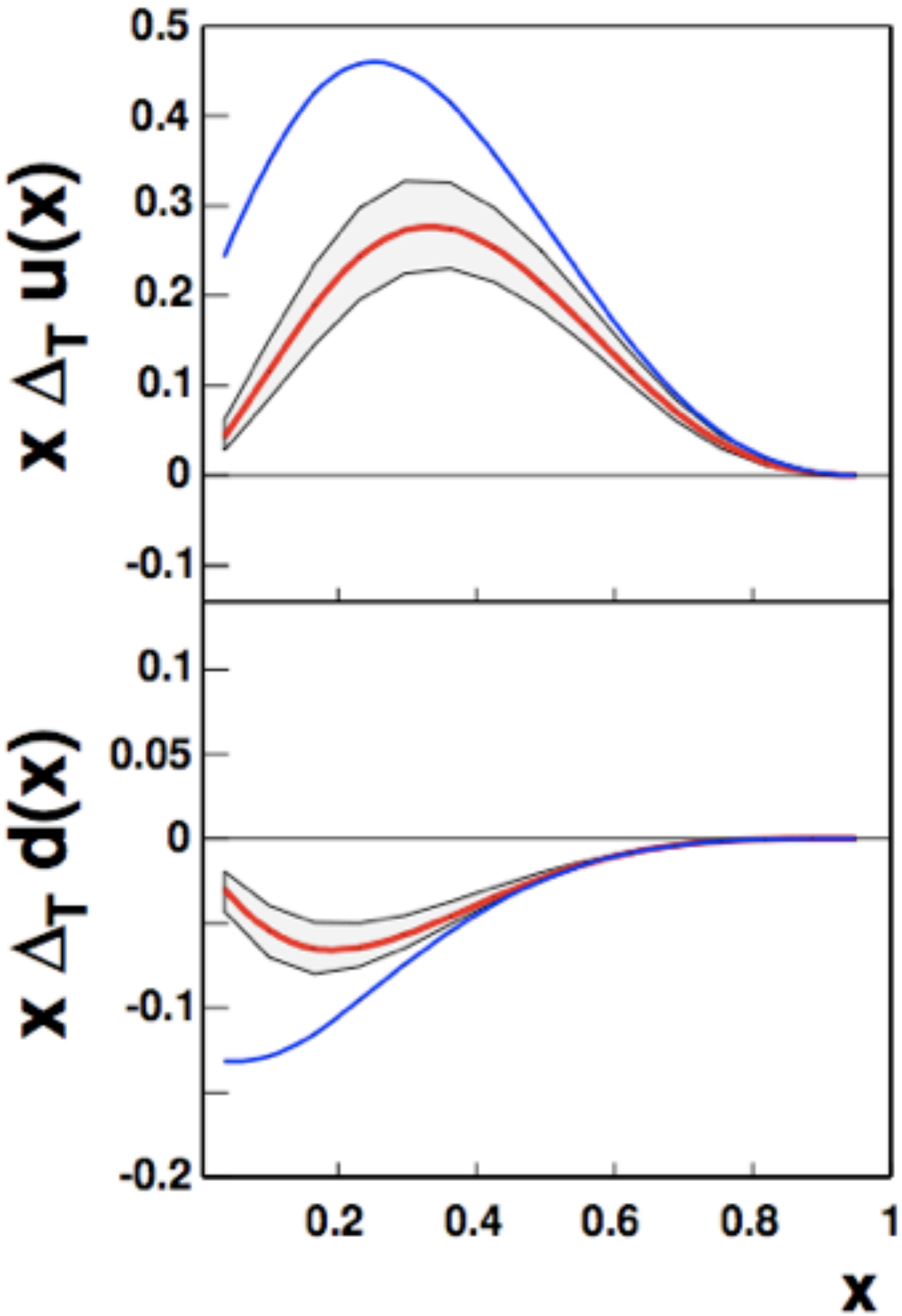




best fit of
Belle data
(independent
information
on the
Collins
functions)

transversity distributions

(blue lines = Soffer's bound)

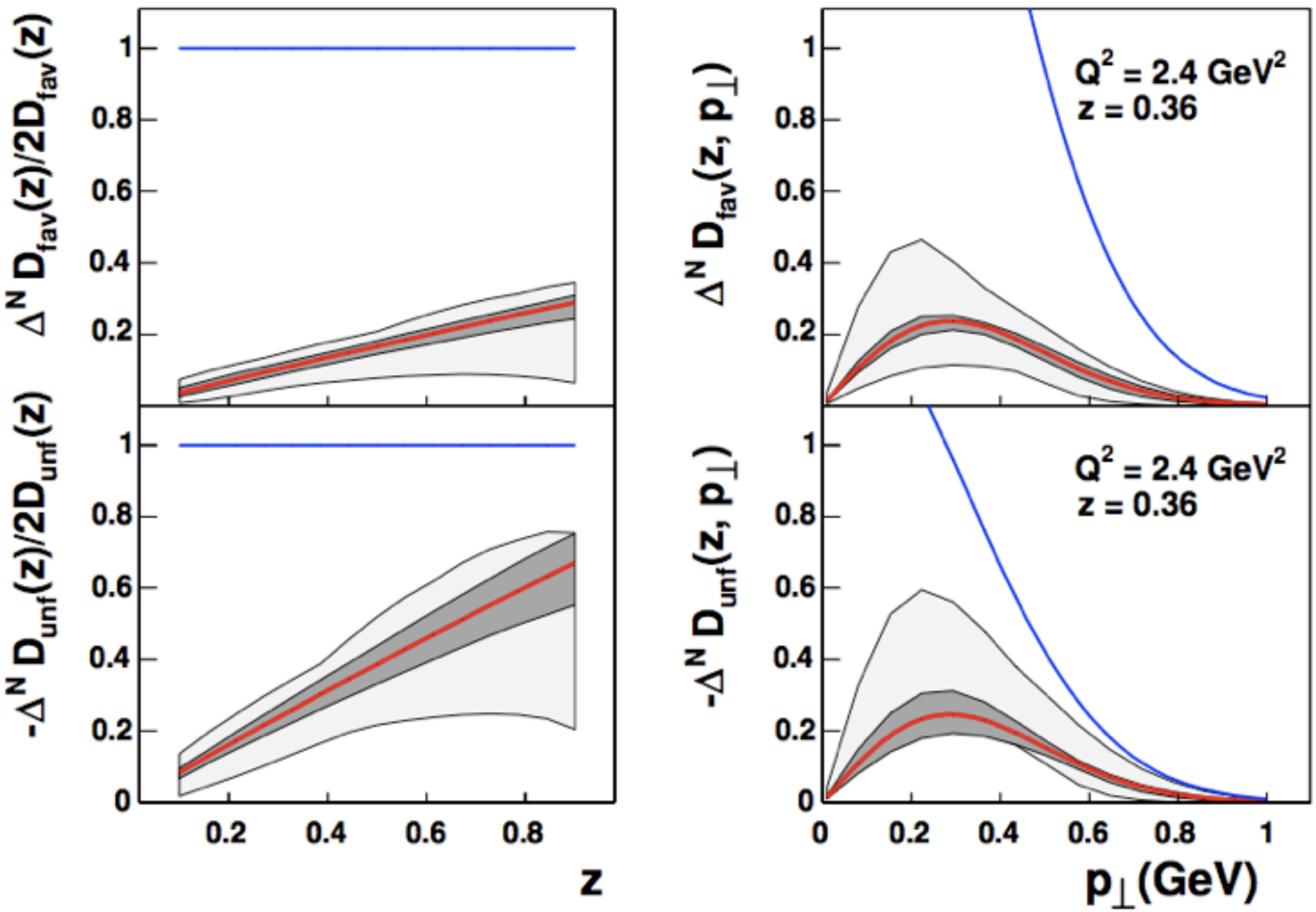


M.A., M. Boglione, U. D'Alesio,
A. Kotzinian, S. Melis, F. Murgia,
A. Prokudin, C. Türk

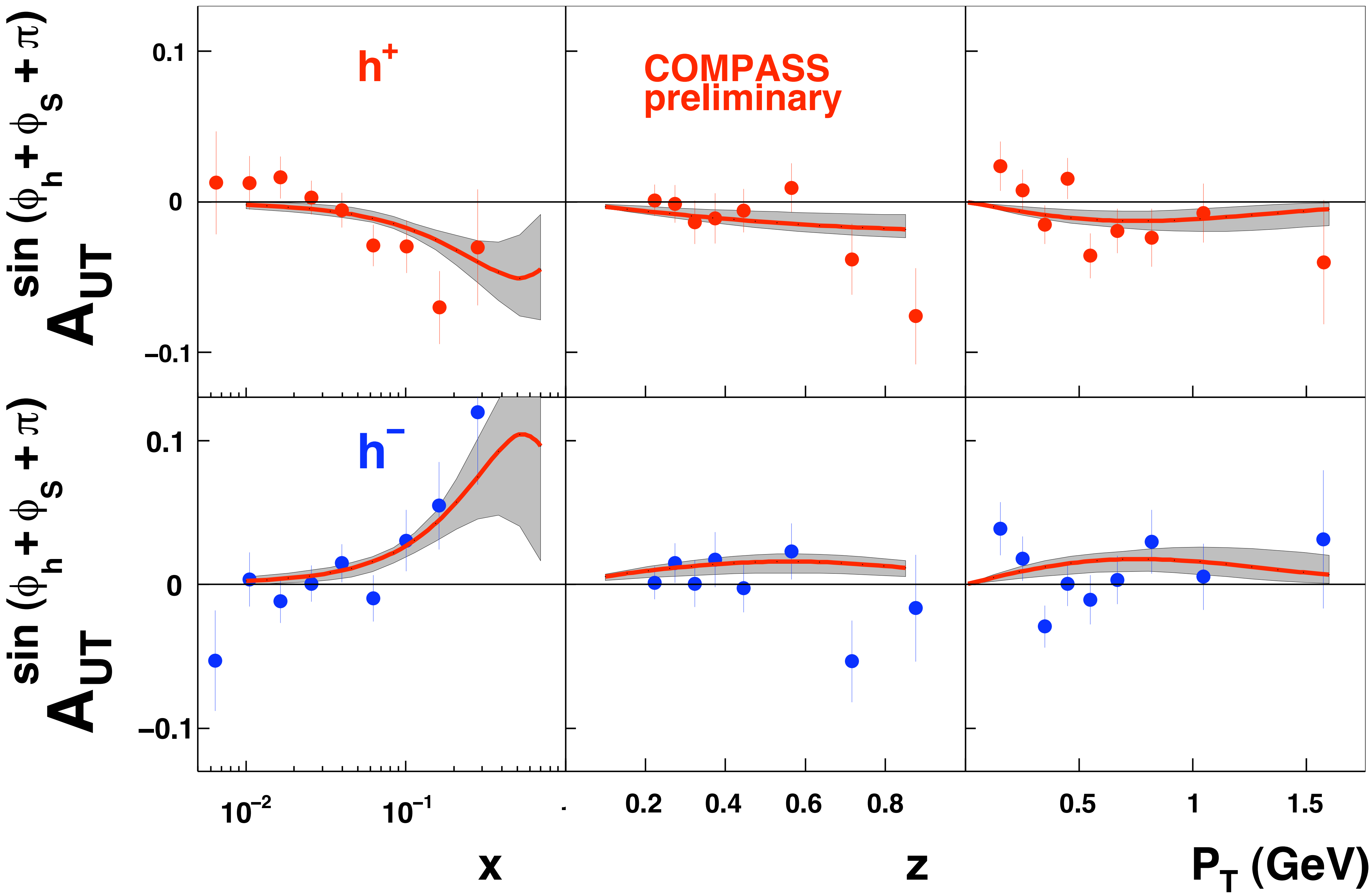
Extraction from SIDIS (HERMES, COMPASS-D) + e^+e^- (Belle) data, $h_1 \otimes H_1^\perp$

$$\Delta_T q(x) = h_1^q(x) =$$
$$\int \mathrm{d}^2\boldsymbol{k}_\perp \left[h_{1T}^q(x, k_\perp^2) + \frac{k_\perp^2}{2m_N^2} h_{1T}^{\perp q}(x, k_\perp^2) \right]$$

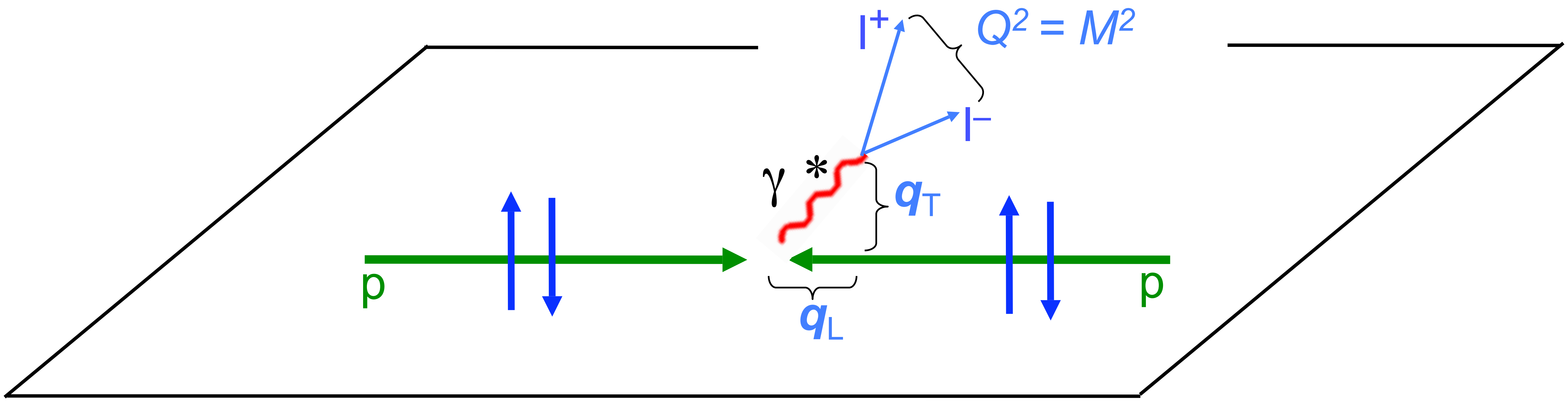
extracted Collins functions



Predictions for COMPASS, with a proton target, and comparison with data



TMDs and SSAs in Drell-Yan processes



factorization holds, two scales, M^2, and q_T

$$d\sigma^{D-Y} = \sum_a f_q(x_1, \boldsymbol{k}_{\perp 1}; Q^2) \otimes f_{\bar{q}}(x_2, \boldsymbol{k}_{\perp 2}; Q^2)\, d\hat{\sigma}^{q\bar{q} \to \ell^+ \ell^-}$$

3 planes: plane $\perp$ to polarization vectors,
$p - \gamma^*$ plane, $l^+ - l^-$ plane
no fragmentation process

Arnold, Metz, Schlegel

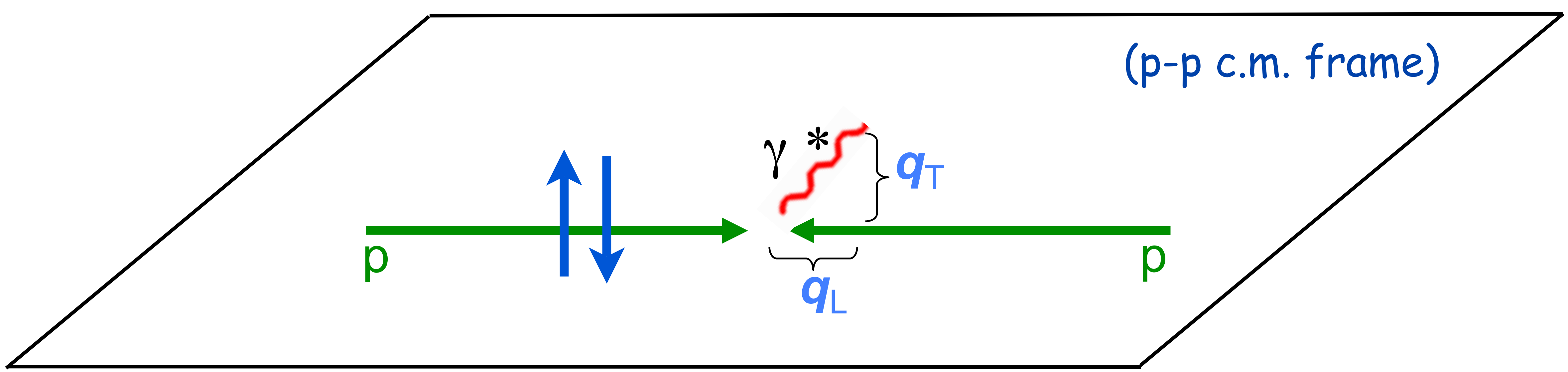
Sivers effect in D-Y processes

By looking at the $d^4\sigma/d^4q$ cross section one can single out the Sivers effect in D-Y processes

$$d\sigma^\uparrow - d\sigma^\downarrow \propto \sum_q \Delta^N f_{q/p^\uparrow}(x_1, \boldsymbol{k}_\perp) \otimes f_{\bar{q}/p}(x_2) \otimes d\hat{\sigma}$$

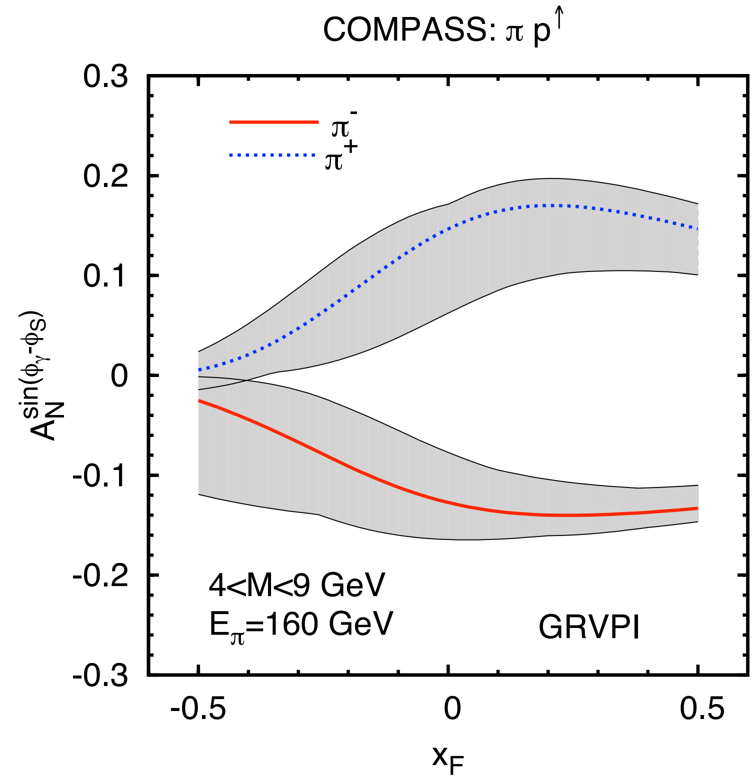
$$q = u, \bar{u}, d, \bar{d}, s, \bar{s}$$

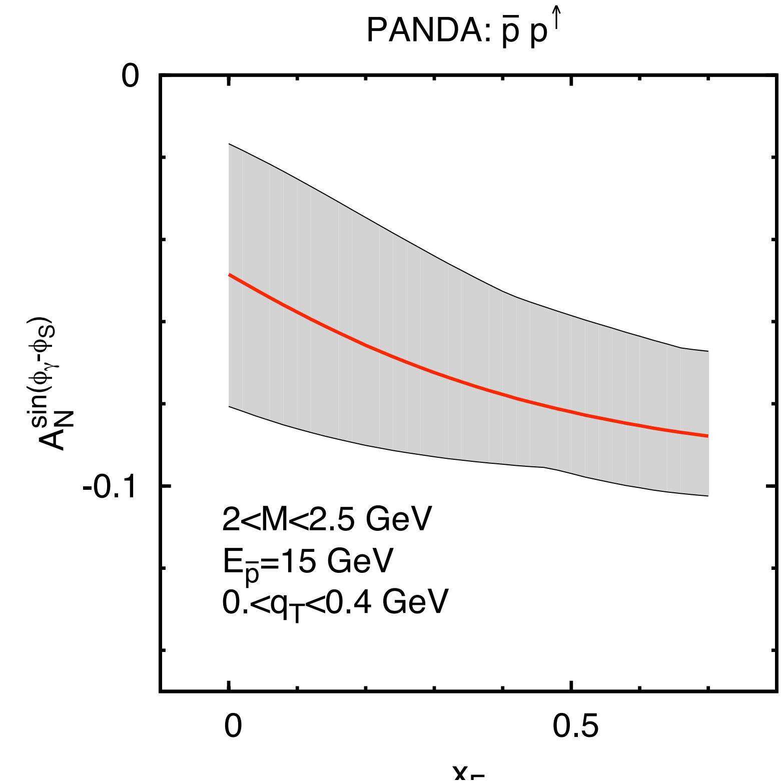
$$A_N^{\sin(\phi_S-\phi_\gamma)} \equiv \frac{2\int_0^{2\pi} d\phi_\gamma \, [d\sigma^\uparrow - d\sigma^\downarrow] \, \sin(\phi_S - \phi_\gamma)}{\int_0^{2\pi} d\phi_\gamma \, [d\sigma^\uparrow + d\sigma^\downarrow]}$$

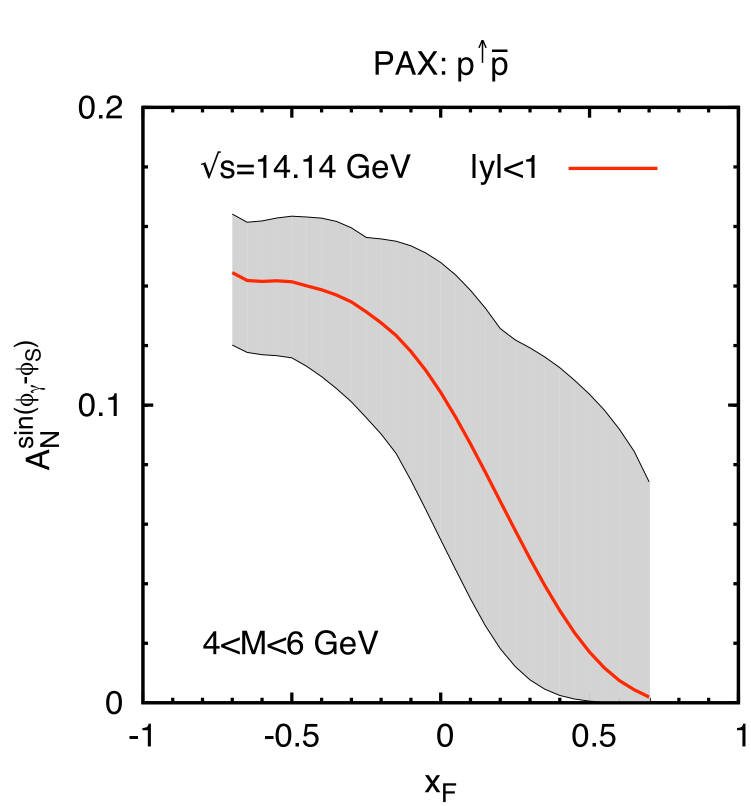


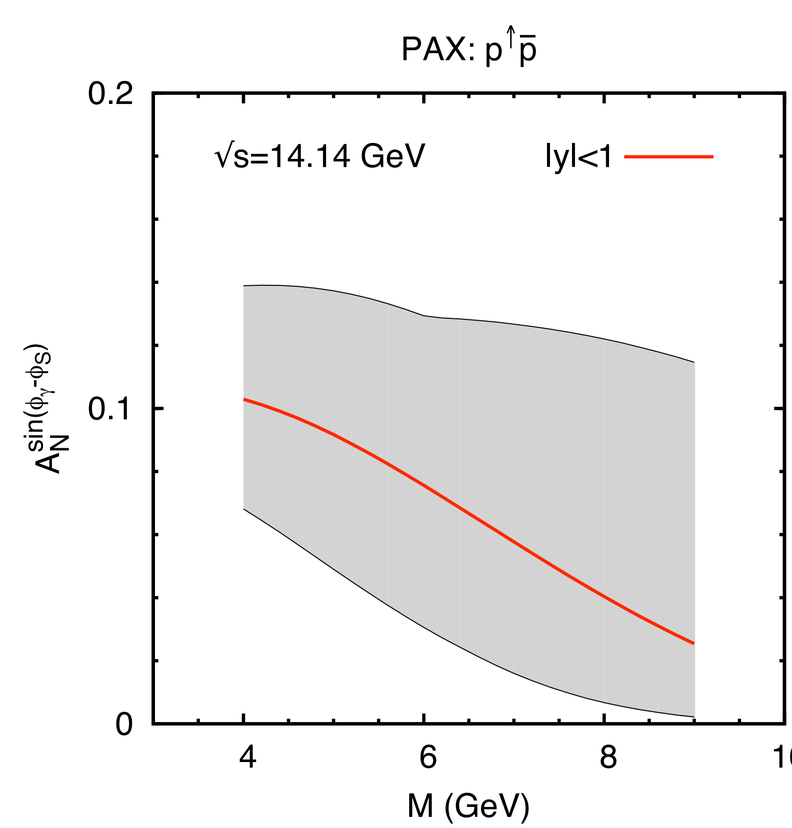
Predictions for A_N

Sivers functions as extracted from SIDIS data, **with opposite sign**







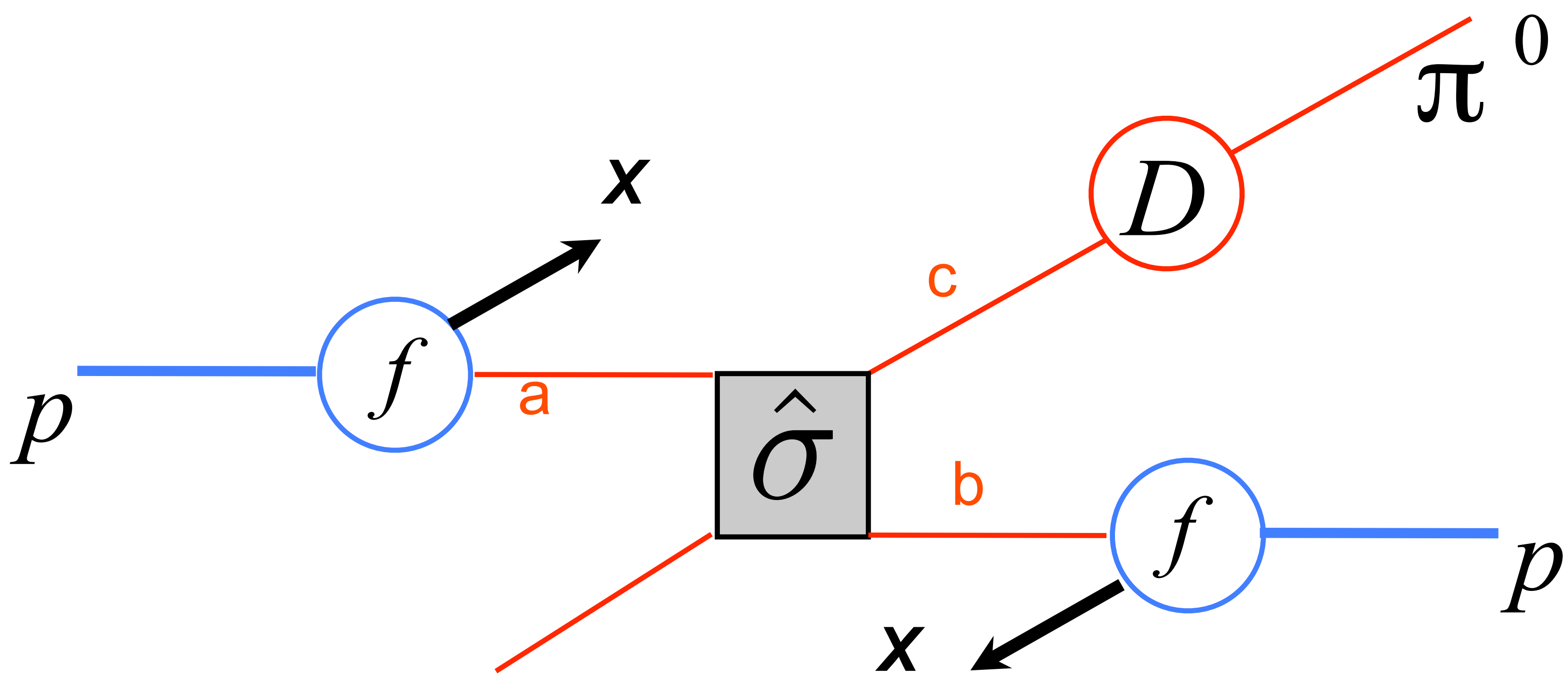


M.A., M. Boglione, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin, e-Print: arXiv:0901.3078

TMDs and SSAs in hadronic processes

Cross section for $p\,p \to \pi^0\,X$ in pQCD, only one scale, P_T

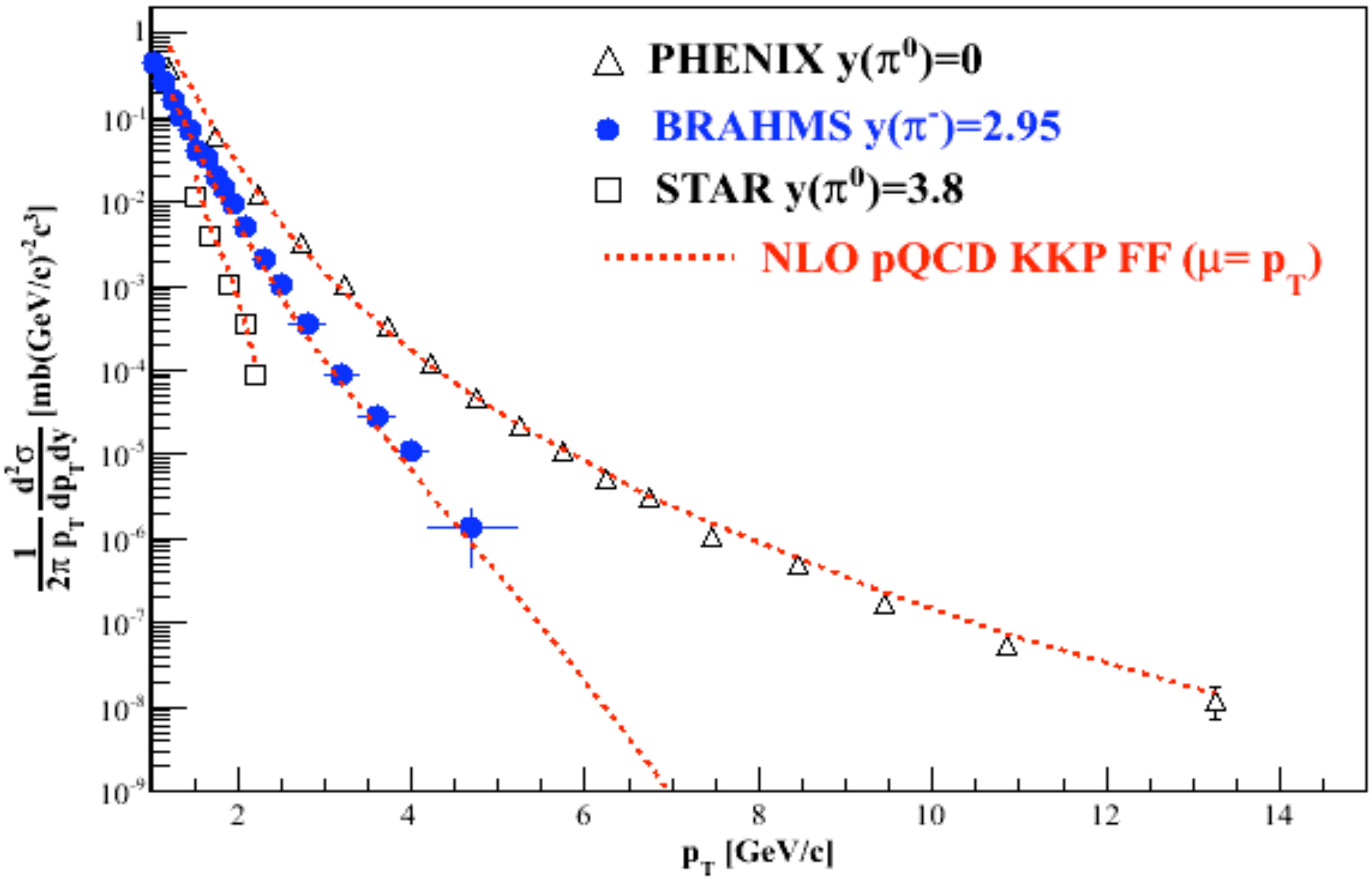
based on factorization theorem
(in collinear configuration)



$$\mathrm{d}\sigma = \sum_{a,b,c,d=q,\bar{q},g} \underbrace{f_{a/p}(x_a) \otimes f_{b/p}(x_b)}_{\text{PDF}} \otimes \mathrm{d}\hat{\sigma}^{ab\to cd} \otimes \underbrace{D_{\pi/c}(z)}_{\text{FF}}$$

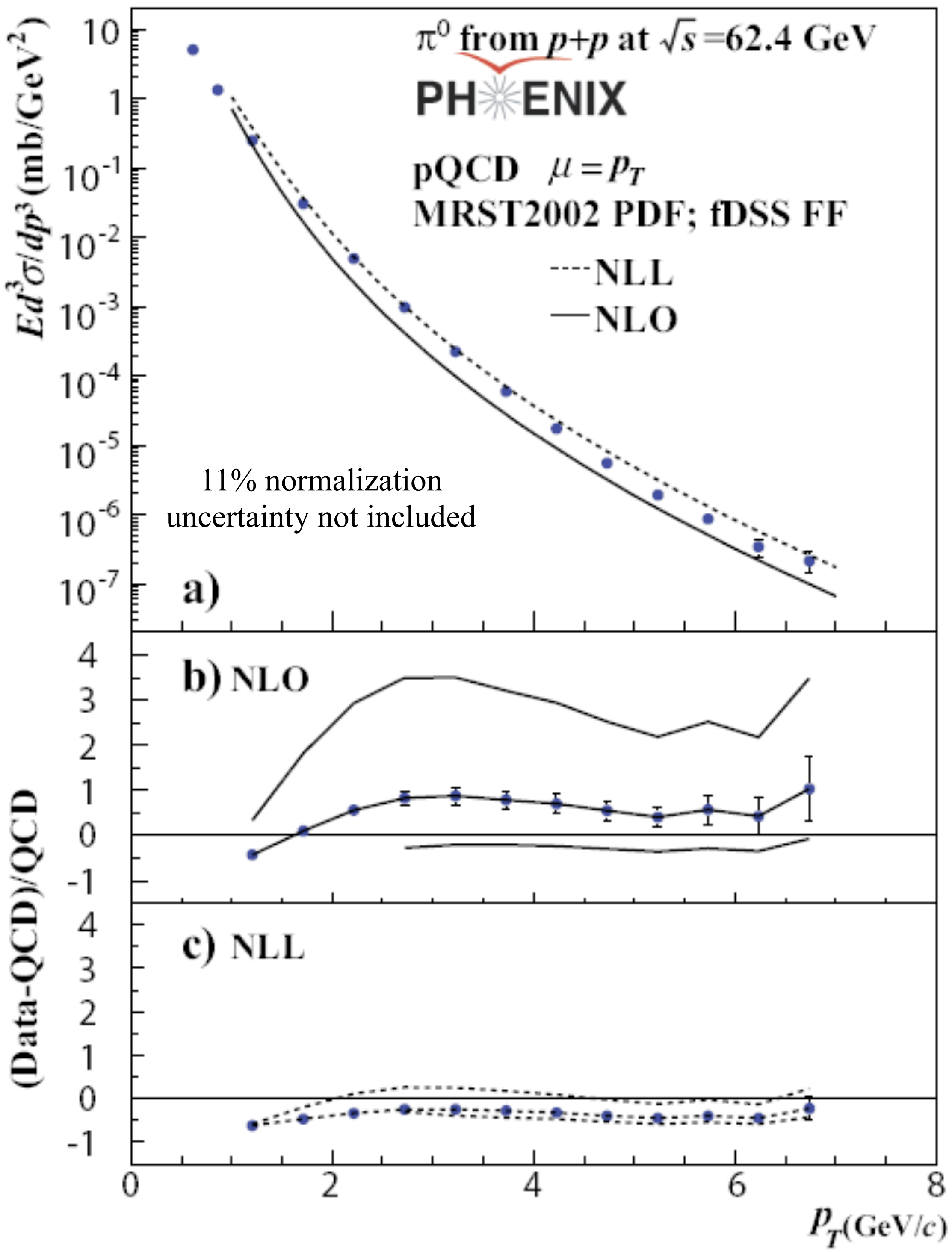
pQCD elementary interactions

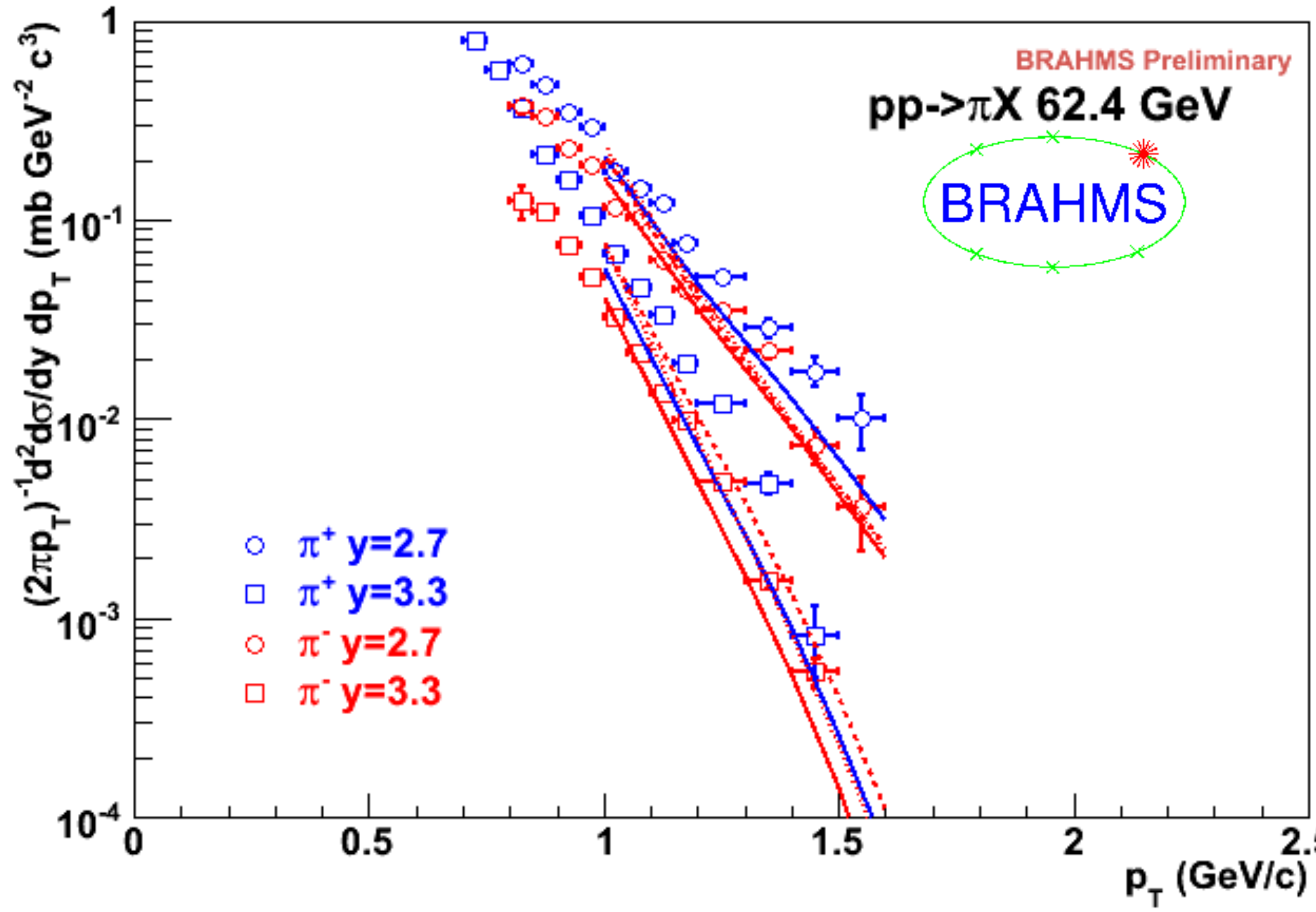
Polarization-averaged cross sections at $\sqrt{s}$=200 GeV



good pQCD description of data at 200 GeV, at all rapidities, down to p_T of 1-2 GeV/c

rather good agreement even at at $\sqrt{s}$=62.4 GeV

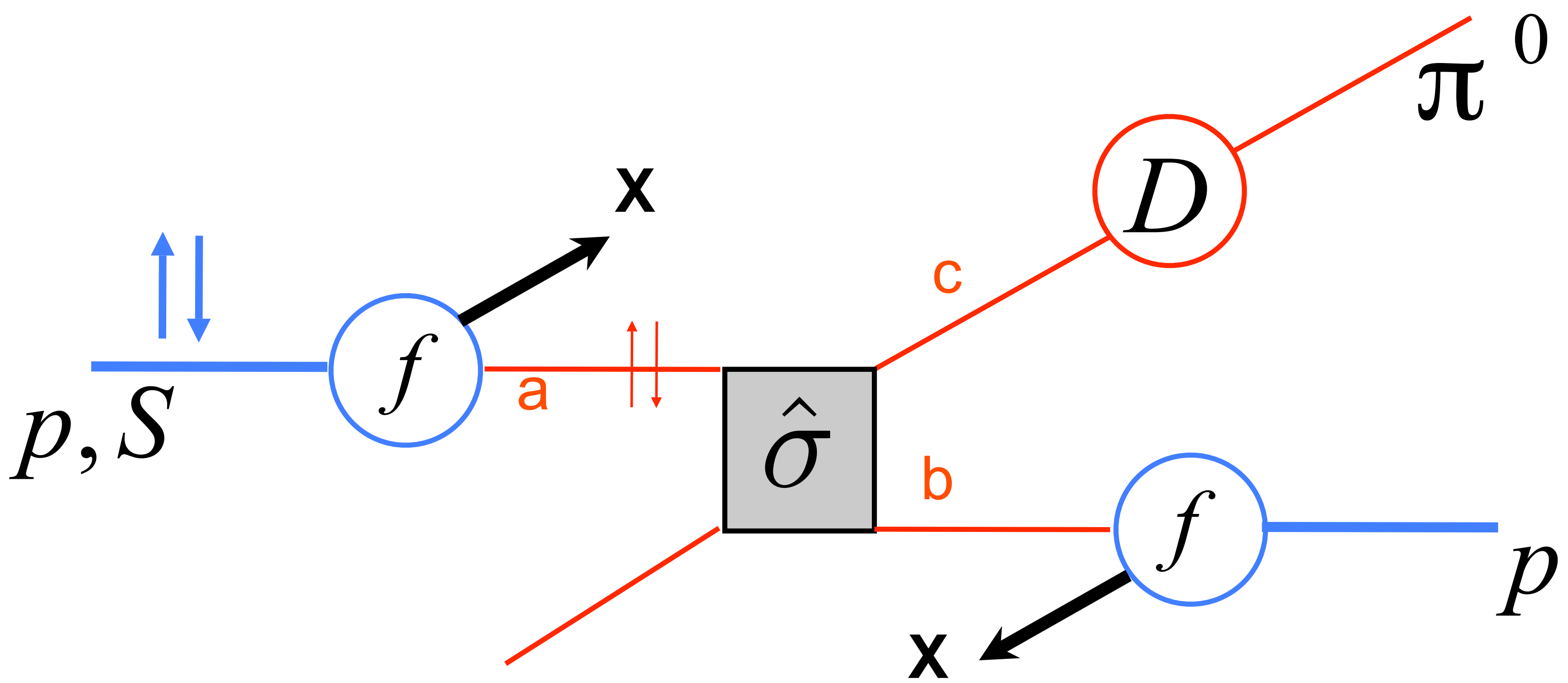




Comparison of NLO pQCD calculations with BRAHMS π data at high rapidity. The calculations are for a scale factor of μ=p_T, KKP (solid) and DSS (dashed) with CTEQ5 and CTEQ6.5.

mid-rapidity pions

SSA?

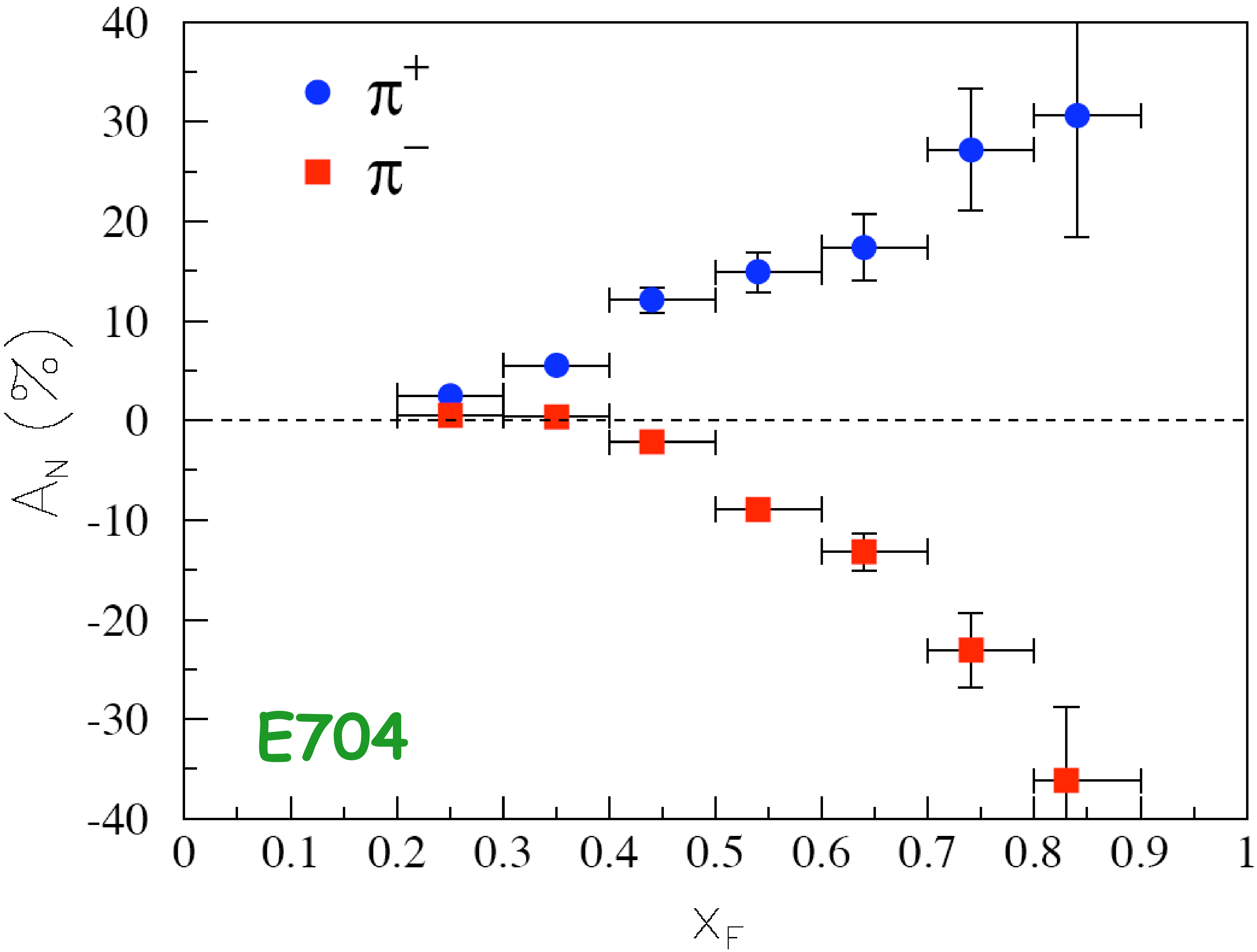


$$d\sigma^{\uparrow} - d\sigma^{\downarrow} = \sum_{a,b,c,d=q,\bar{q},g} \underbrace{\Delta_T f_a}_{\text{transversity}} \otimes f_b \otimes \underbrace{[d\hat{\sigma}^{\uparrow} - d\hat{\sigma}^{\downarrow}]}_{\text{pQCD elementary SSA}} \otimes \underbrace{D_{\pi/c}}_{\text{FF}}$$

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto \hat{a}_N \propto \frac{m_q}{E_q} \alpha_s$$

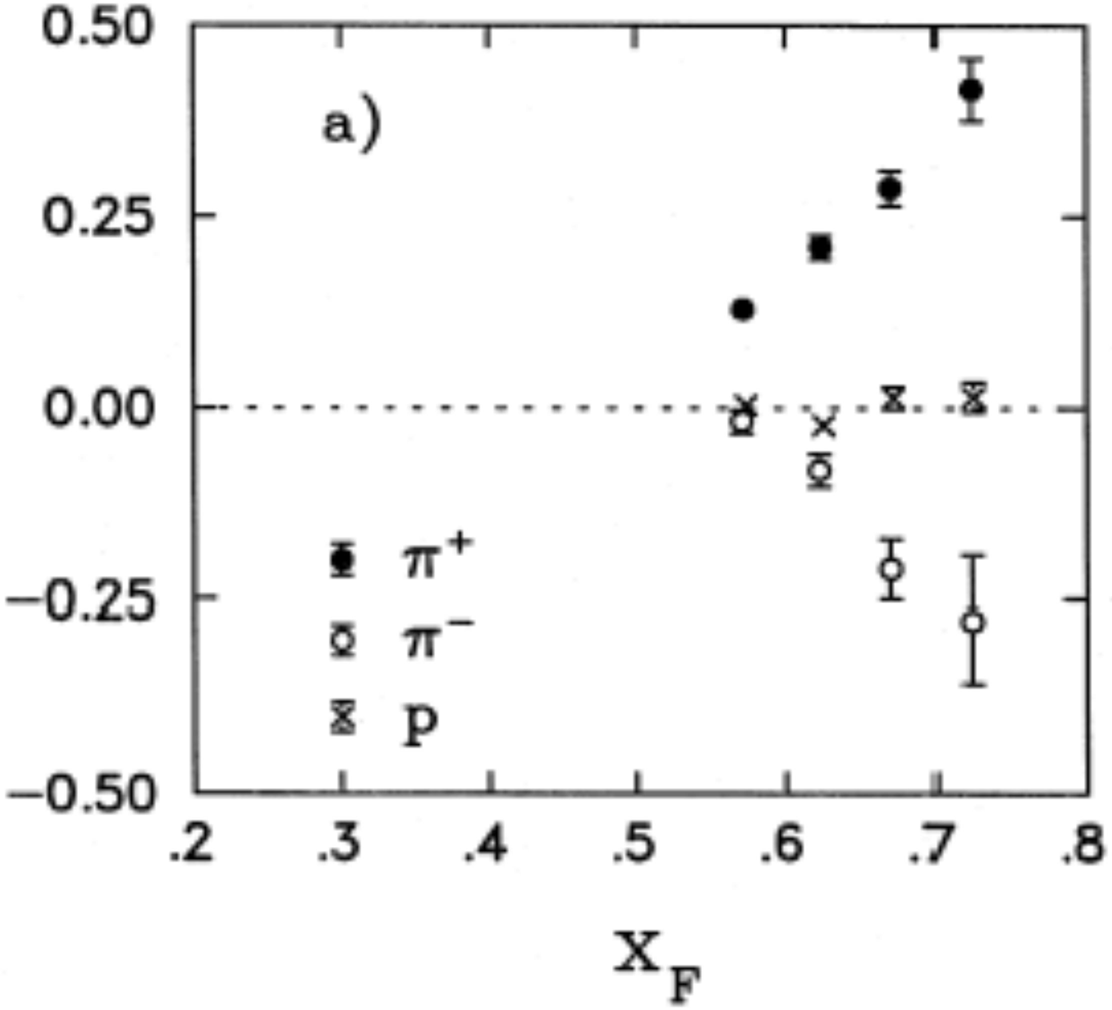
was considered almost a theorem

but, ...



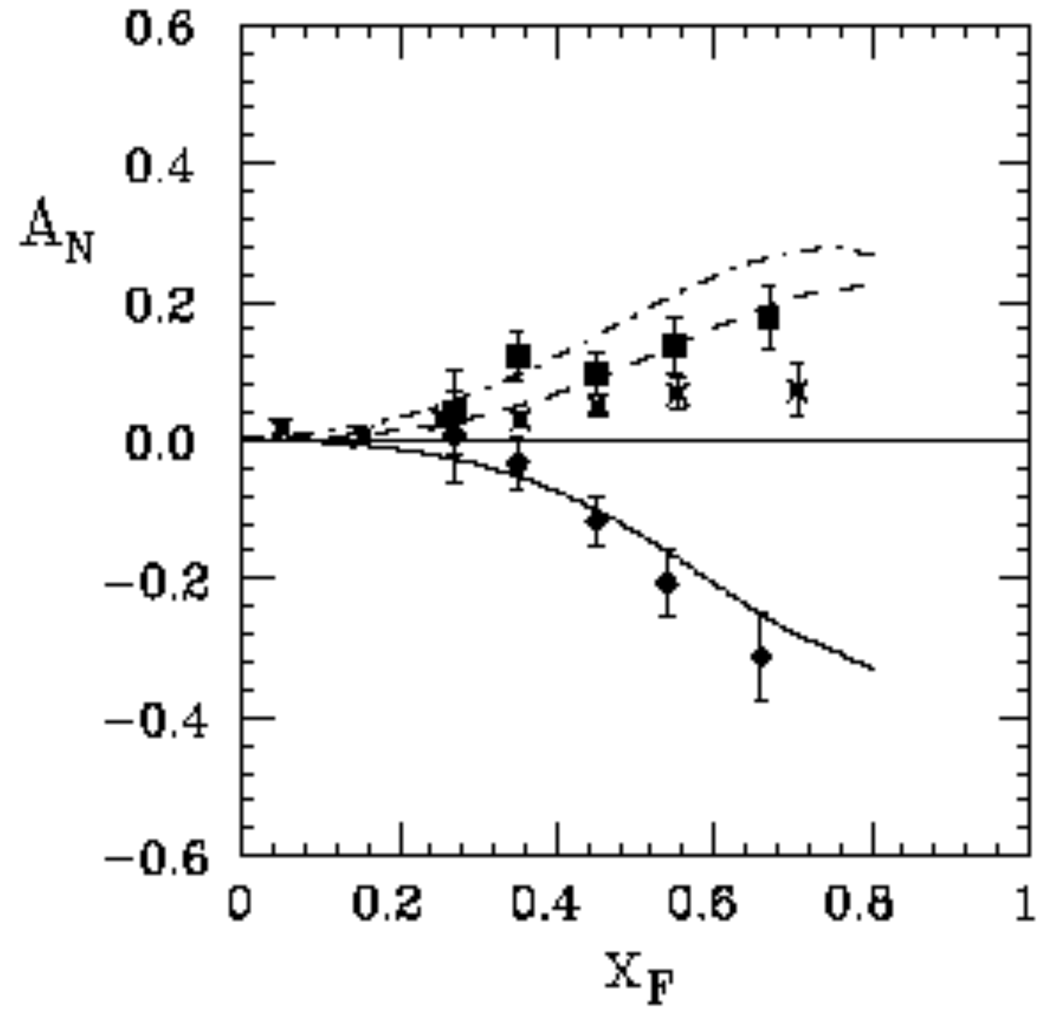
E704 $\sqrt{s}$ = 20 GeV 0.7 < p_T < 2.0

$$p^{\uparrow}\, p \rightarrow \pi\, X$$



BNL-AGS
$\sqrt{s}$ = 6.6 GeV
0.6 < p_T < 1.2

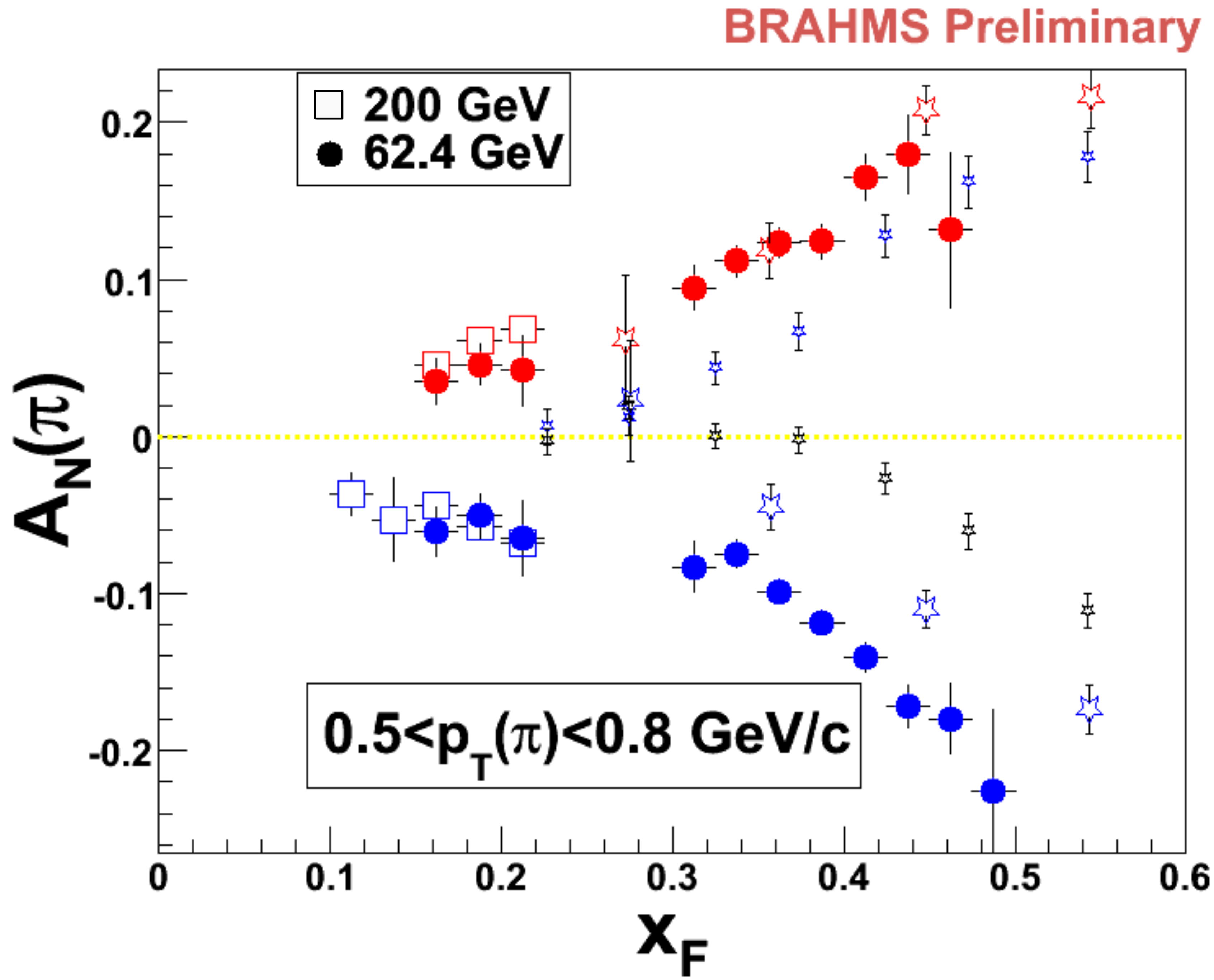
$$\bar{p}^{\uparrow}\, p \rightarrow \pi\, X$$



E704 $\sqrt{s}$ = 20 GeV
0.7 < p_T < 2.0

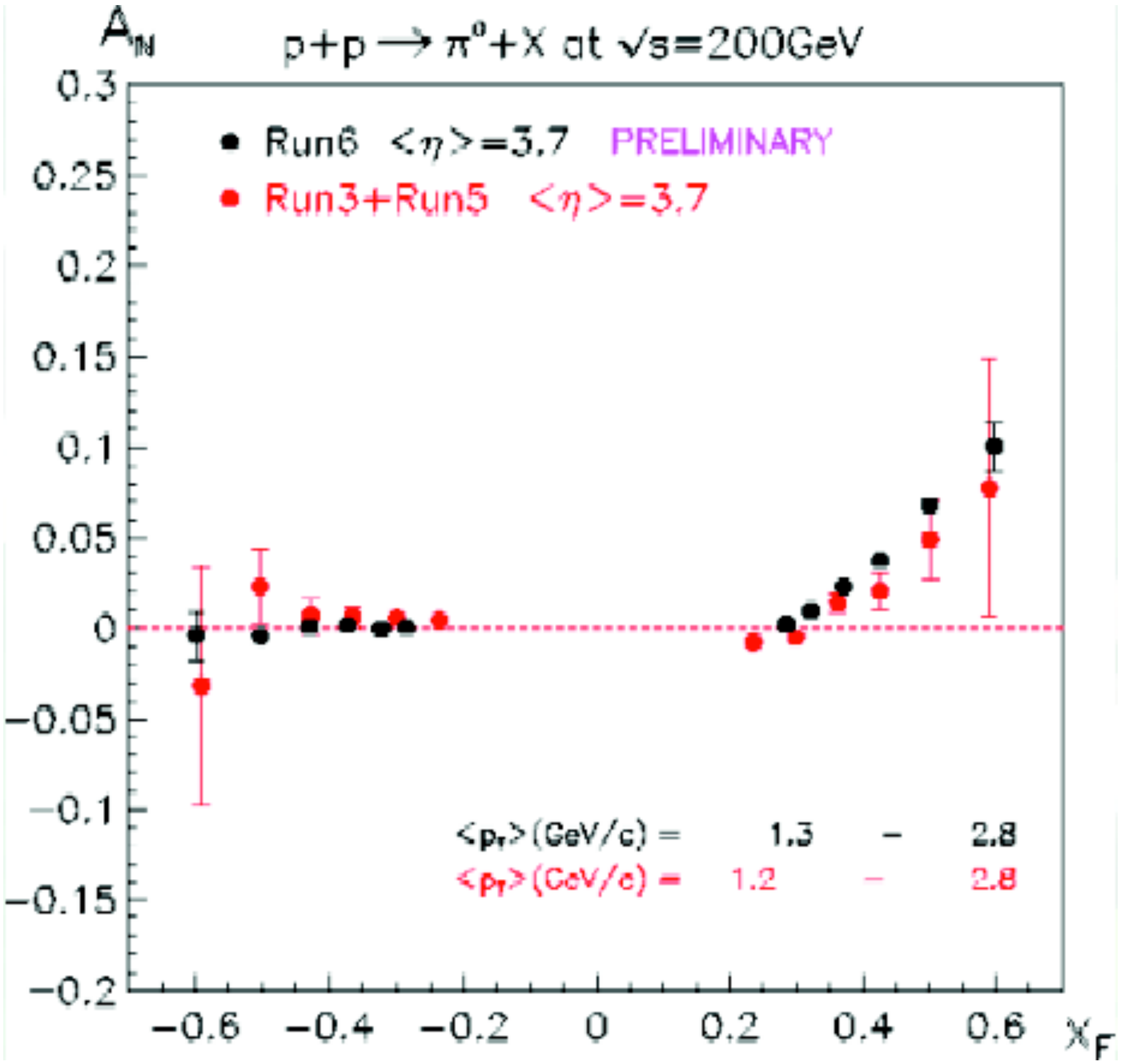
Unifying 62.4 and 200 GeV, BRAHMS + E704

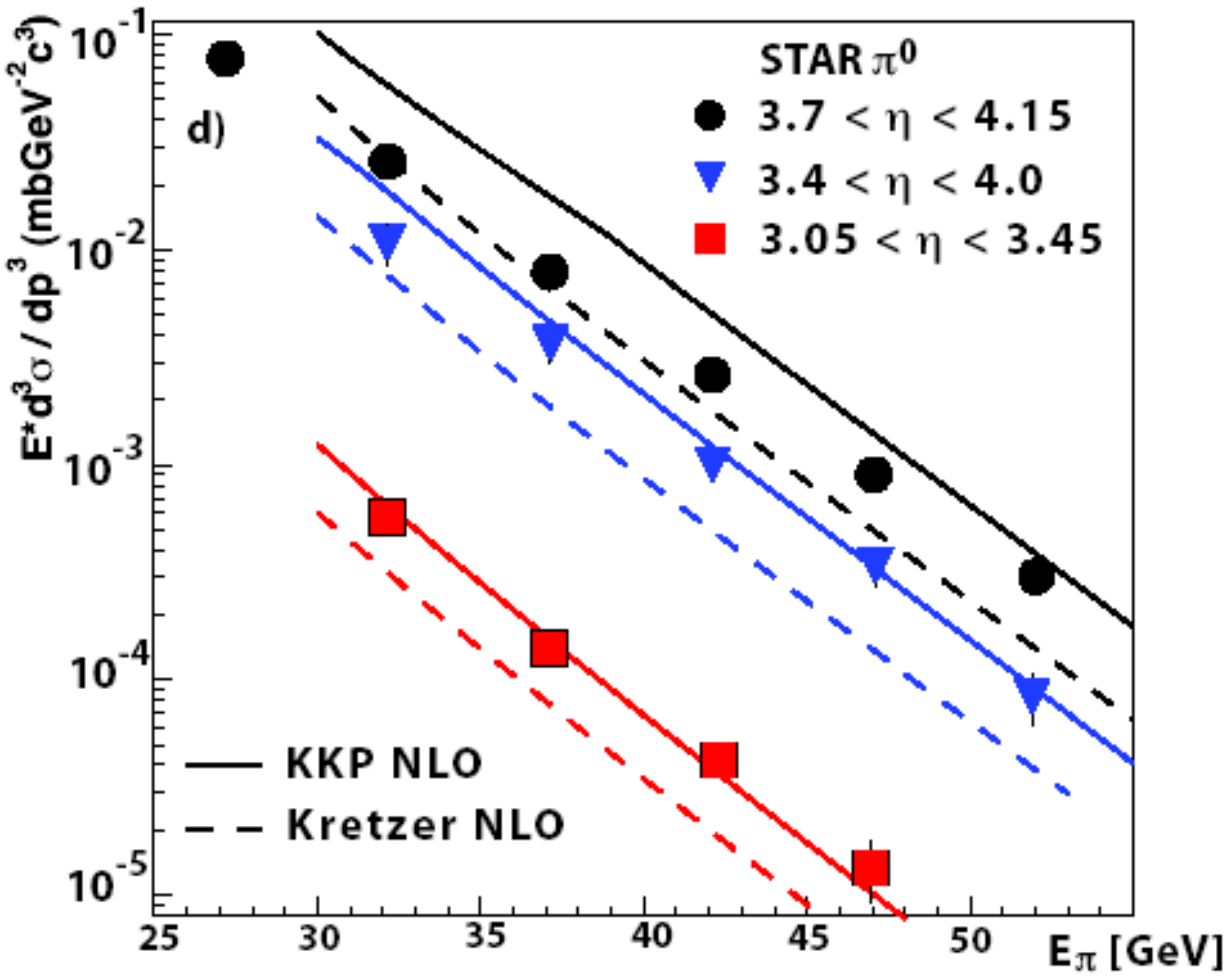
(C. Aidala talk at transversity 2008, Ferrara)



E704 data – all p_T (small stars); p_T>0.7 GeV/c (large stars)

good description of unpolarized cross-section, A_N ... ?



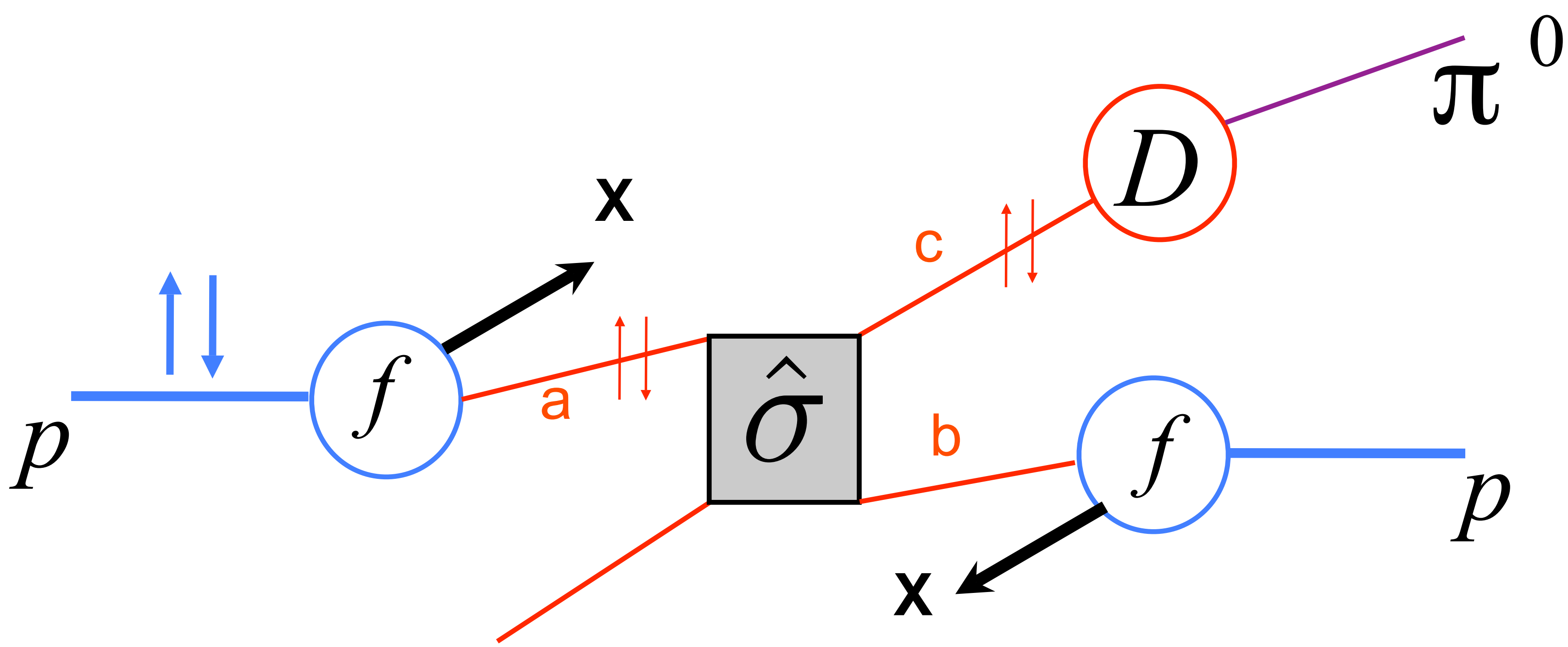


STAR-RHIC $\sqrt{s}$ = 200 GeV $1.2 < p_T < 2.8$

SSA in hadronic processes: TMDs, higher-twist correlations?

Two main different (?) approaches

1. Generalization of collinear scheme (assuming factorization)



$$d\sigma^{\uparrow} = \sum_{a,b,c=q,\bar{q},g} \underbrace{f_{a/p^{\uparrow}}(x_a, \boldsymbol{k}_{\perp a})} \otimes \underbrace{f_{b/p}(x_b, \boldsymbol{k}_{\perp b})} \otimes d\hat{\sigma}^{ab\to cd}(\boldsymbol{k}_{\perp a}, \boldsymbol{k}_{\perp b}) \otimes \underbrace{D_{\pi/c}(z, \boldsymbol{p}_{\perp\pi})}$$

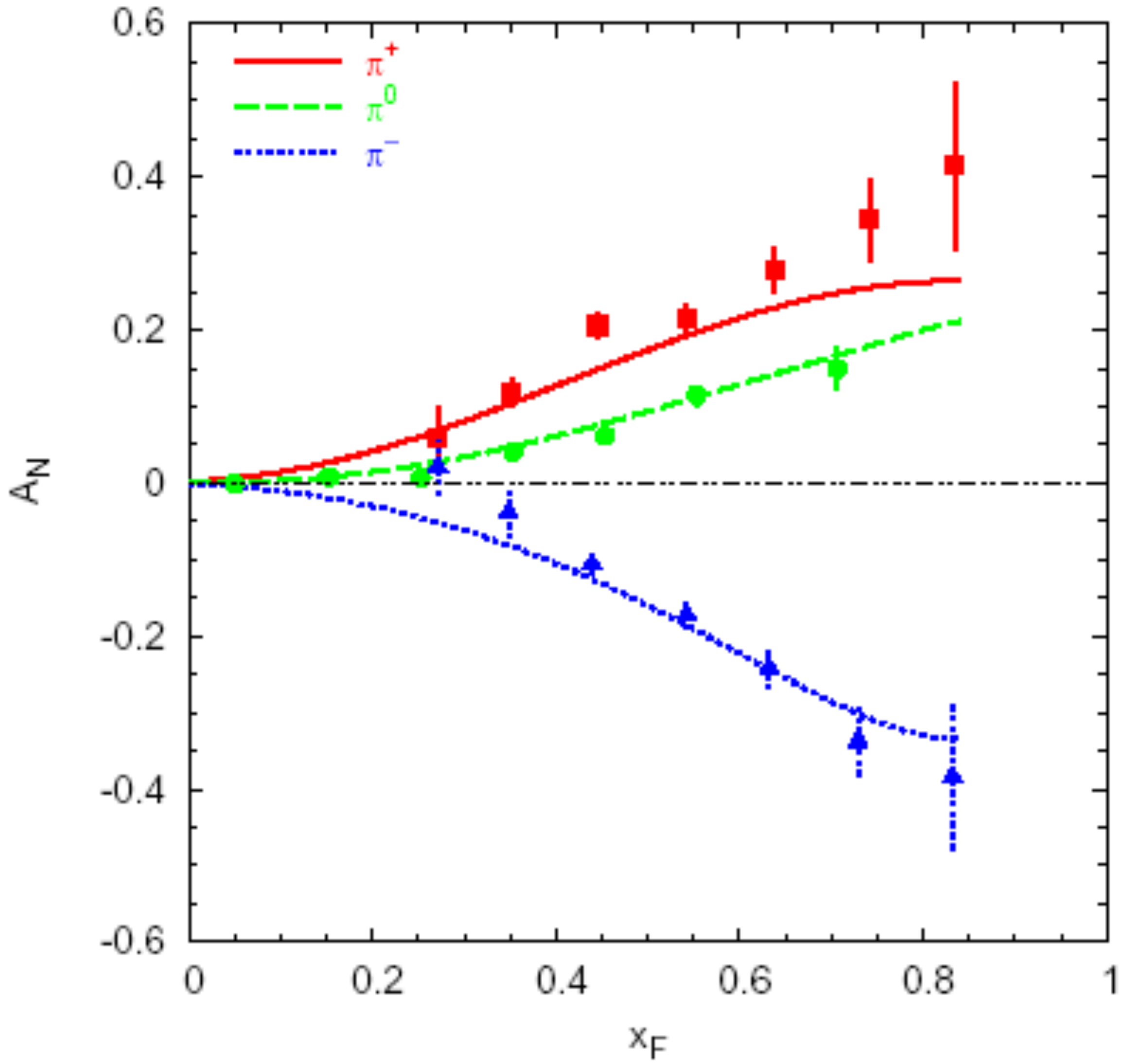
single spin effects in TMDs

M.A., M. Boglione, U. D'Alesio, E. Leader, S. Melis, F. Murgia, A. Prokudin, ...

Field-Feynman

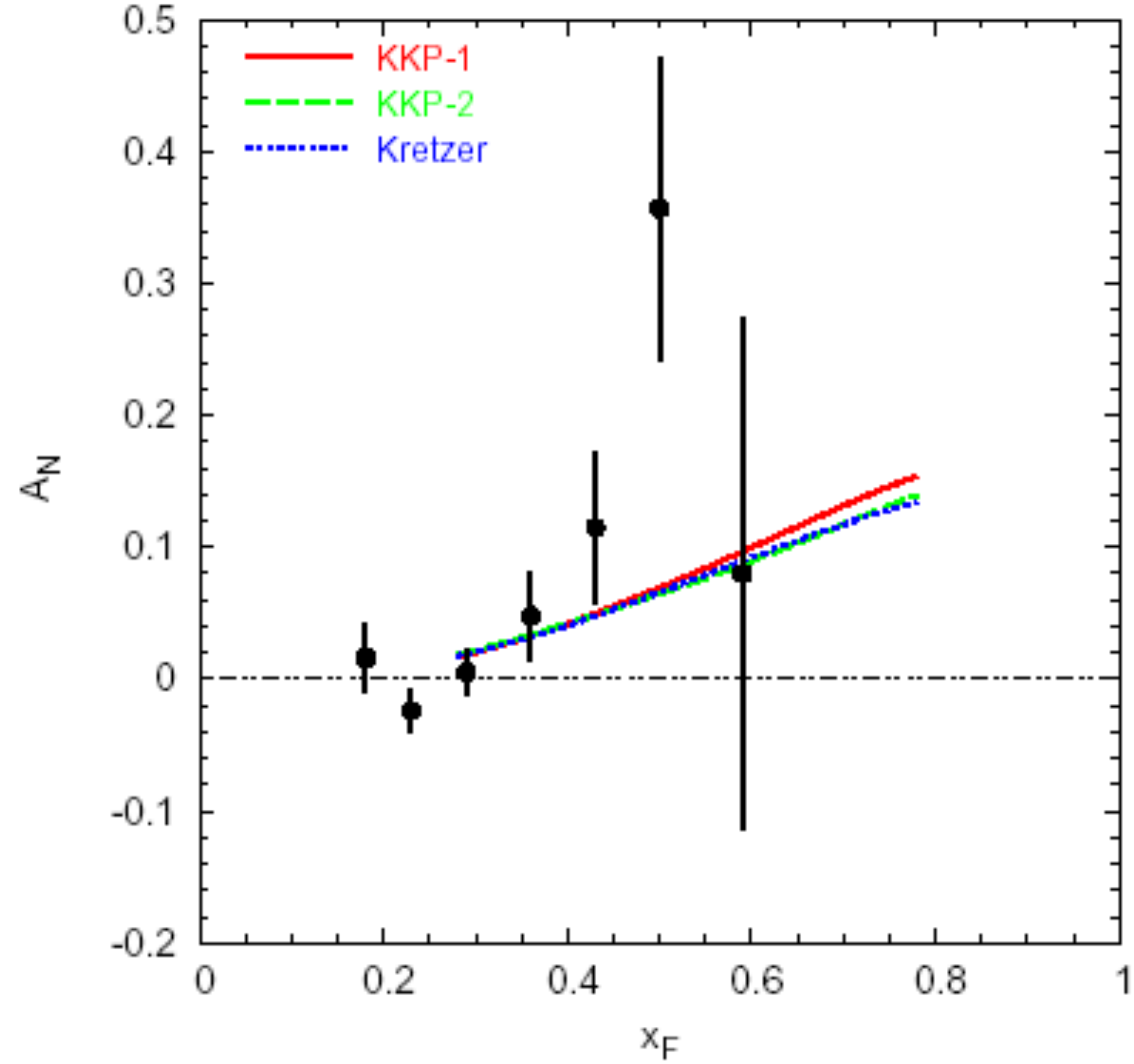
U. D'Alesio, F. Murgia

E704 data



fit

STAR data



prediction

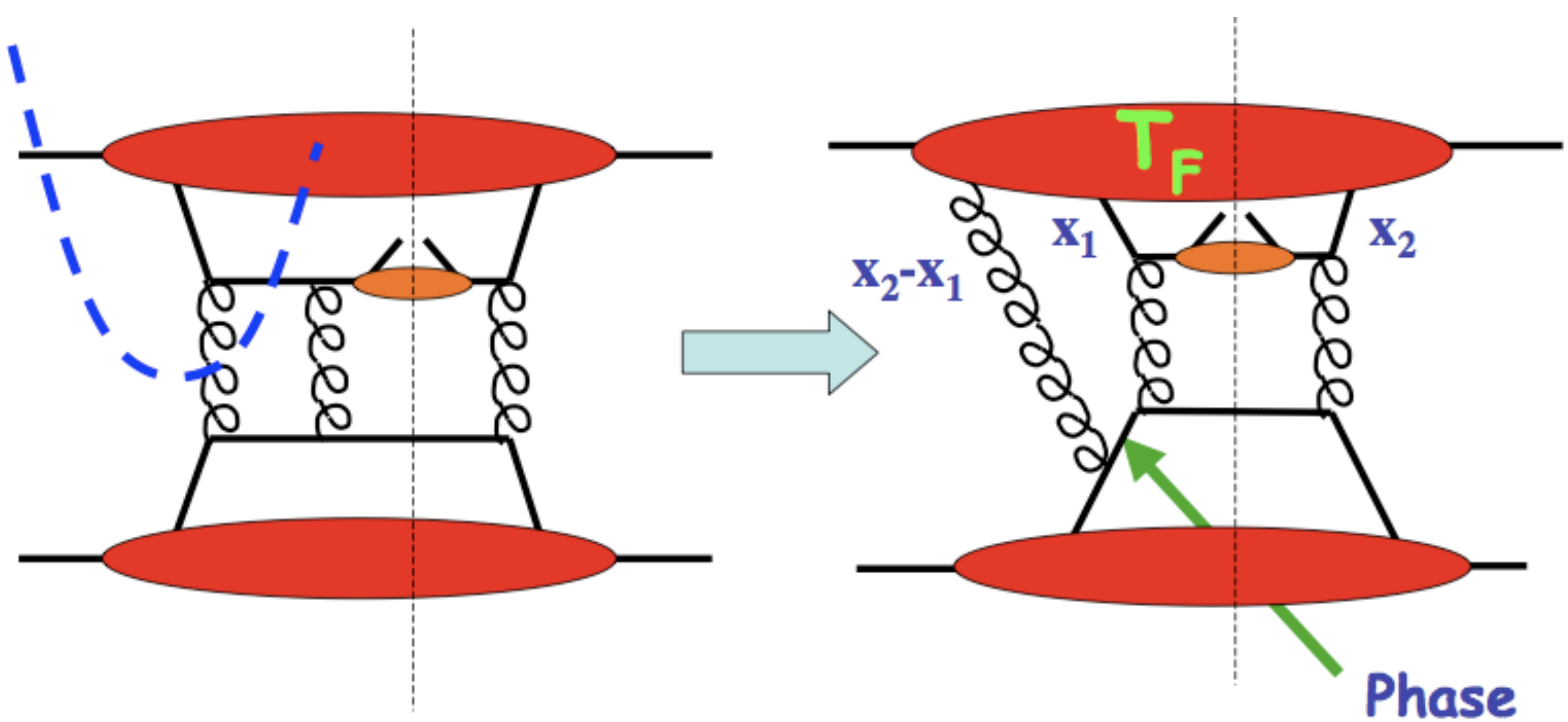
Sivers effect $p\,p \to \pi\,X$

2. Higher-twist partonic correlations

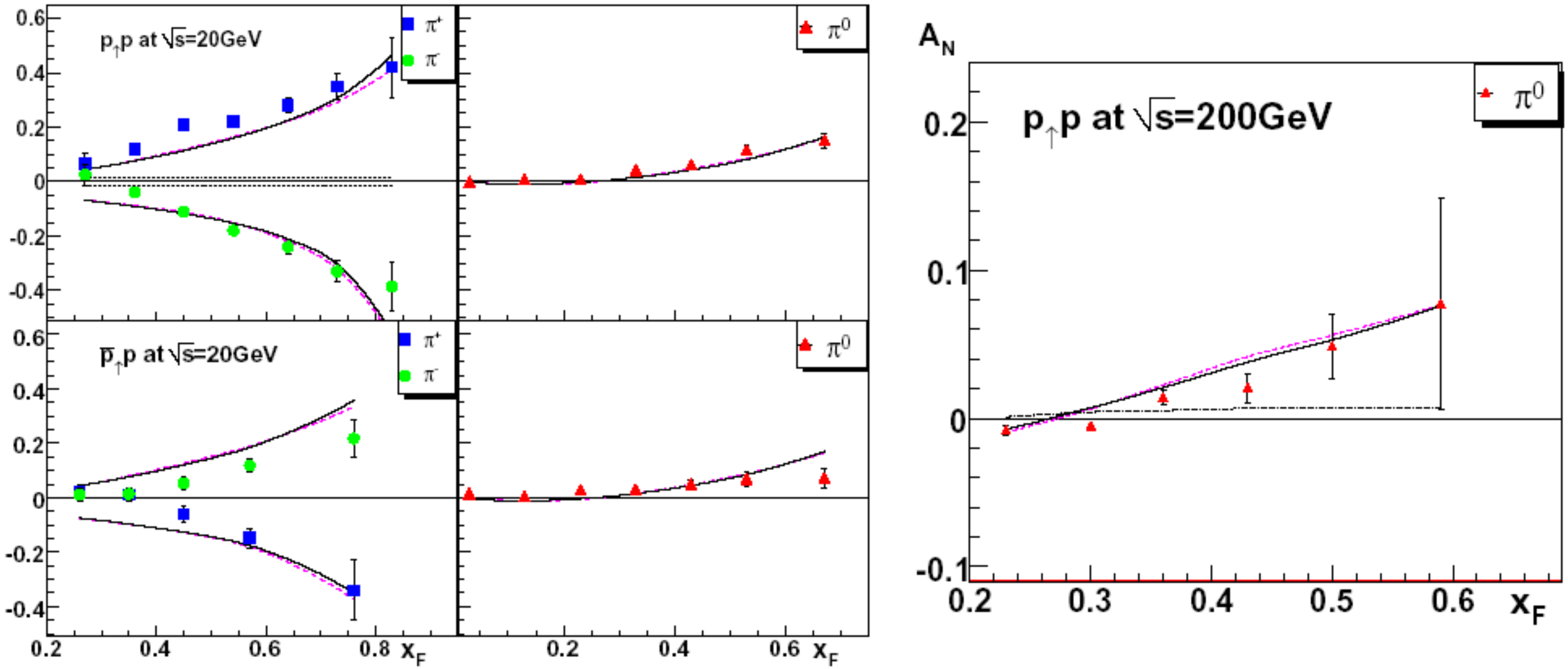
(Efremov, Teryaev; Qiu, Sterman; Kouvaris, Vogelsang, Yuan; Bacchetta, Bomhof, Mulders, Pijlman; Koike ...)

contribution to SSA $(A^{\uparrow}B \to h\,X)$

$$\mathrm{d}\Delta\sigma \propto \sum_{a,b,c} \underbrace{T_a(k_1, k_2, \boldsymbol{S}_\perp)}_{\text{twist-3 functions}} \otimes f_{b/B}(x_b) \otimes \underbrace{H^{ab\to c}(k_1, k_2)}_{\text{hard interactions}} \otimes D_{h/c}(z)$$



courtesy of W. Vogelsang

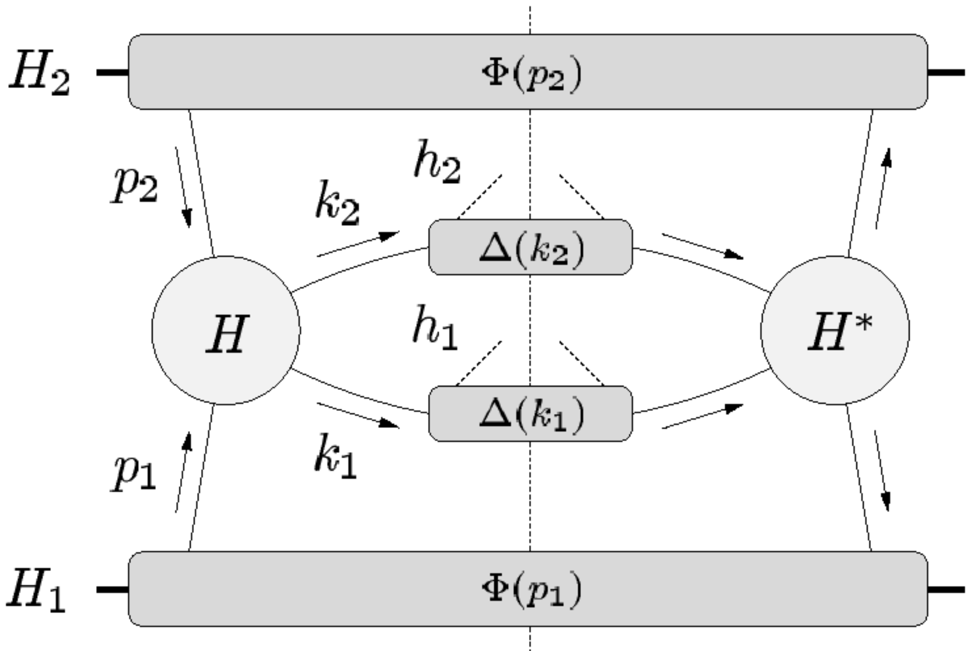


fits of E704 and STAR data

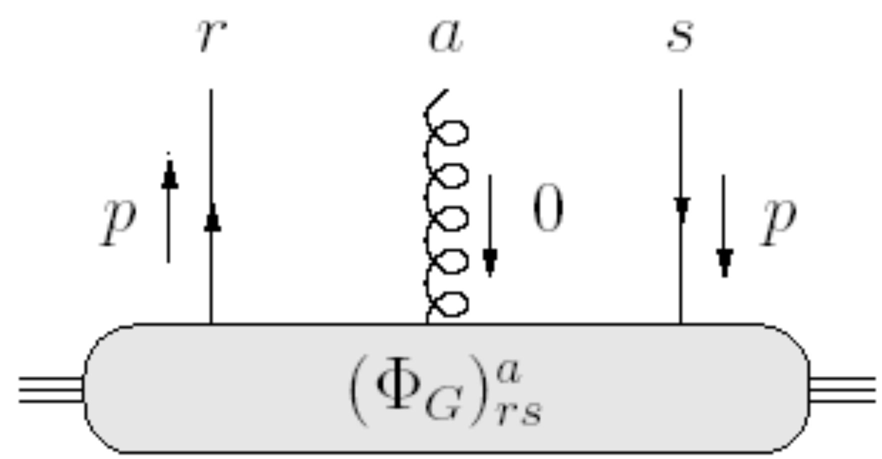
Kouvaris, Qiu, Vogelsang, Yuan

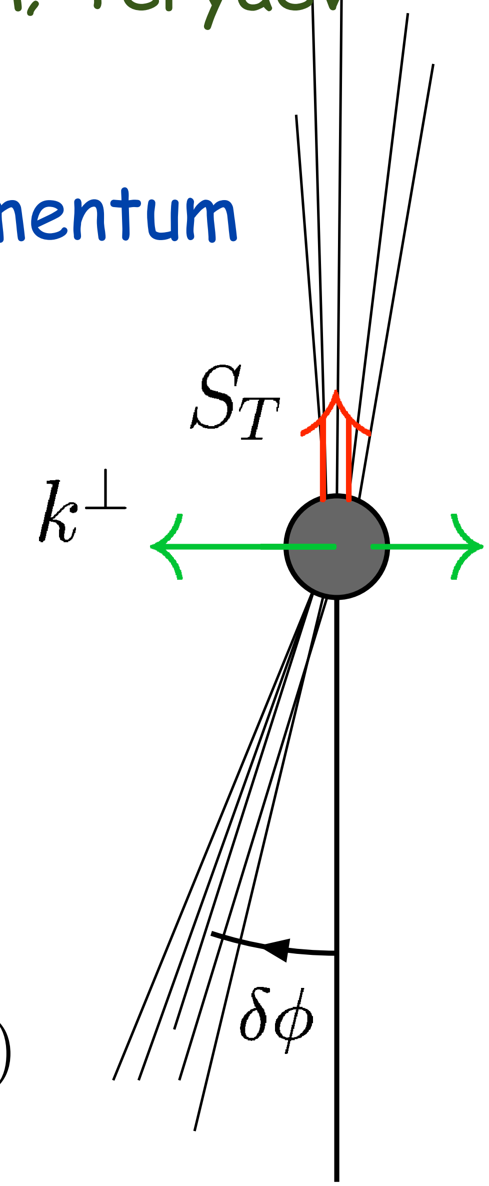
SSA in pp → jet + jet + X, $H_1\,H_2 \rightarrow h_1\,h_2\,X$

Bacchetta, Bomhof, Mulders, Pijlman; Boer,Vogelsang, Yuan; Teryaev



$k^{\perp}$ = jet pair transverse momentum





Sivers contribution to SSA $(T_a \propto f_{1T}^{\perp(1)})$

$$\mathrm{d}\Delta\sigma \propto \sum_{a,b,c} f_{1T}^{\perp(1)}(x_1) \otimes f_{b/H_2}(x_2) \otimes \mathrm{d}\hat{\sigma}_{[a]b\rightarrow cd} \otimes D_{h_1/c}(z_1)\, D_{h_2/d}(z_2)$$

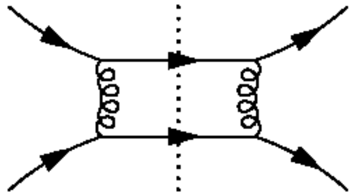
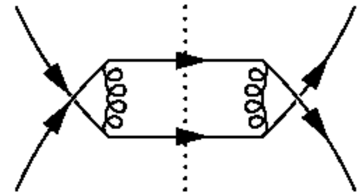
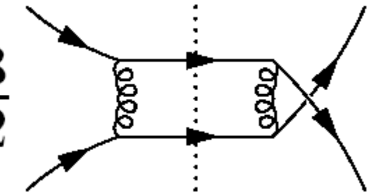
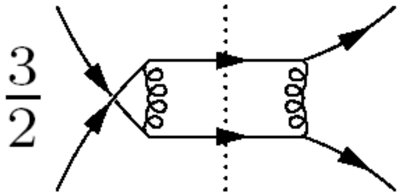
gluonic pole cross sections take into account gauge links

$$\mathrm{d}\hat{\sigma}_{[a]b\rightarrow cd} = \sum_D C_G^{[D]}\, \mathrm{d}\hat{\sigma}^D_{ab\rightarrow cd}$$

$C_G^{[D]}$ Diagram dependent Gauge link Colour factors

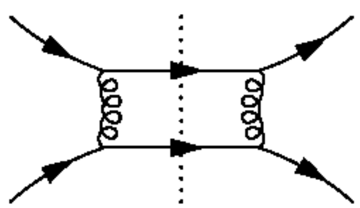
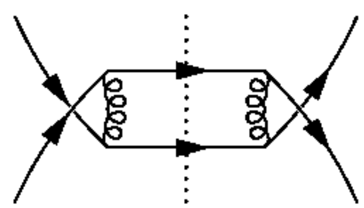
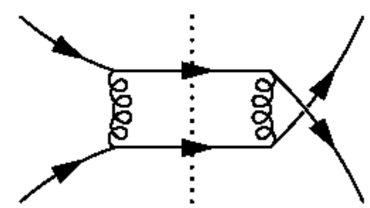
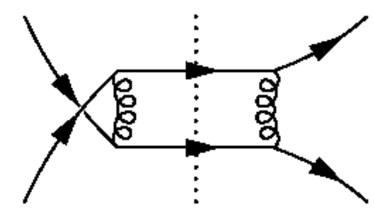
(breaking of factorization?)

Gluonic pole cross sections and SSA in $H_1 H_2 \to h_1 h_2 X$

$\dfrac{d\hat{\sigma}_{[q]q\to qq}}{d\hat{t}} = \dfrac{1}{2}$  $+\ \dfrac{1}{2}$  $+\ \dfrac{3}{2}$  $+\ \dfrac{3}{2}$ 

$$= \frac{4\pi\alpha_S^2}{9\hat{s}^2}\left\{ \frac{\hat{s}^2+\hat{u}^2}{2\hat{t}^2} + \frac{\hat{s}^2+\hat{t}^2}{2\hat{u}^2} + \frac{\hat{s}^2}{\hat{t}\hat{u}} \right\}$$

to be compared with the usual cross section

$\dfrac{d\hat{\sigma}_{qq\to qq}}{d\hat{t}} =$  $+$  $-$  $-$ 

$$= \frac{4\pi\alpha_S^2}{9\hat{s}^2}\left\{ \frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2} + \frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2} - \frac{2}{3}\,\frac{\hat{s}^2}{\hat{t}\hat{u}} \right\}$$

$$\mathrm{d}\hat{\sigma}_{[\ell]q\to\ell q} = \mathrm{d}\hat{\sigma}_{\ell q\to\ell q} \qquad\qquad \mathrm{d}\hat{\sigma}_{[q]\bar{q}\to\ell^+\ell^-} = -\mathrm{d}\hat{\sigma}_{q\bar{q}\to\ell^+\ell^-}$$

Crucial role of gauge-links in TMDs

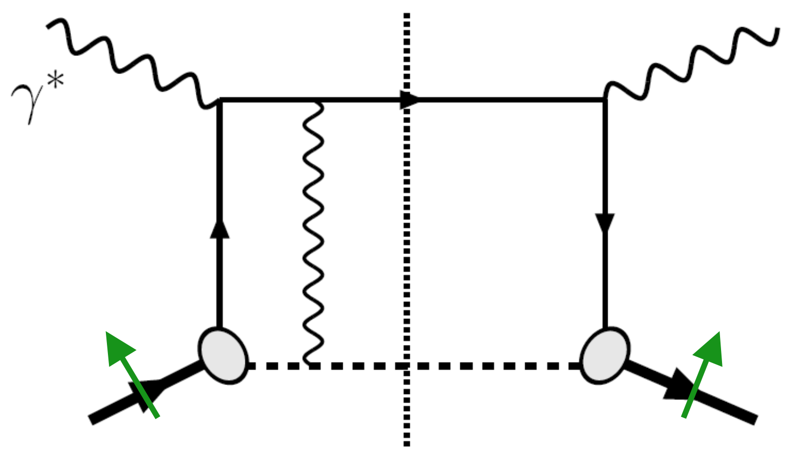
Brodsky, Hwang, Schmidt; Collins; Belitsky, Ji, Yuan; Boer, Mulders, Pijlman

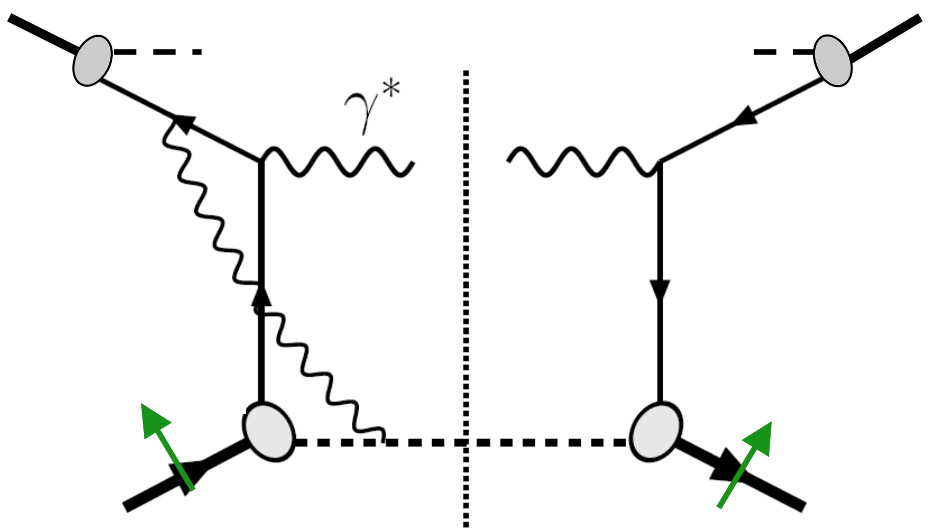
- profound implication:

process-dependece of Sivers functions

$$f_{\mathrm{DY}}^{\mathrm{Sivers}}(x,k_\perp) = - f_{\mathrm{DIS}}^{\mathrm{Sivers}}(x,k_\perp)$$

DIS: "attractive" **DY:** "repulsive"





- hugely important in QCD -- tests a lot of what we know about description of hard processes

W. Vogelsang's talk at Beijing, June 2008

questions.....

Could we test TMD factorization in one scale processes?

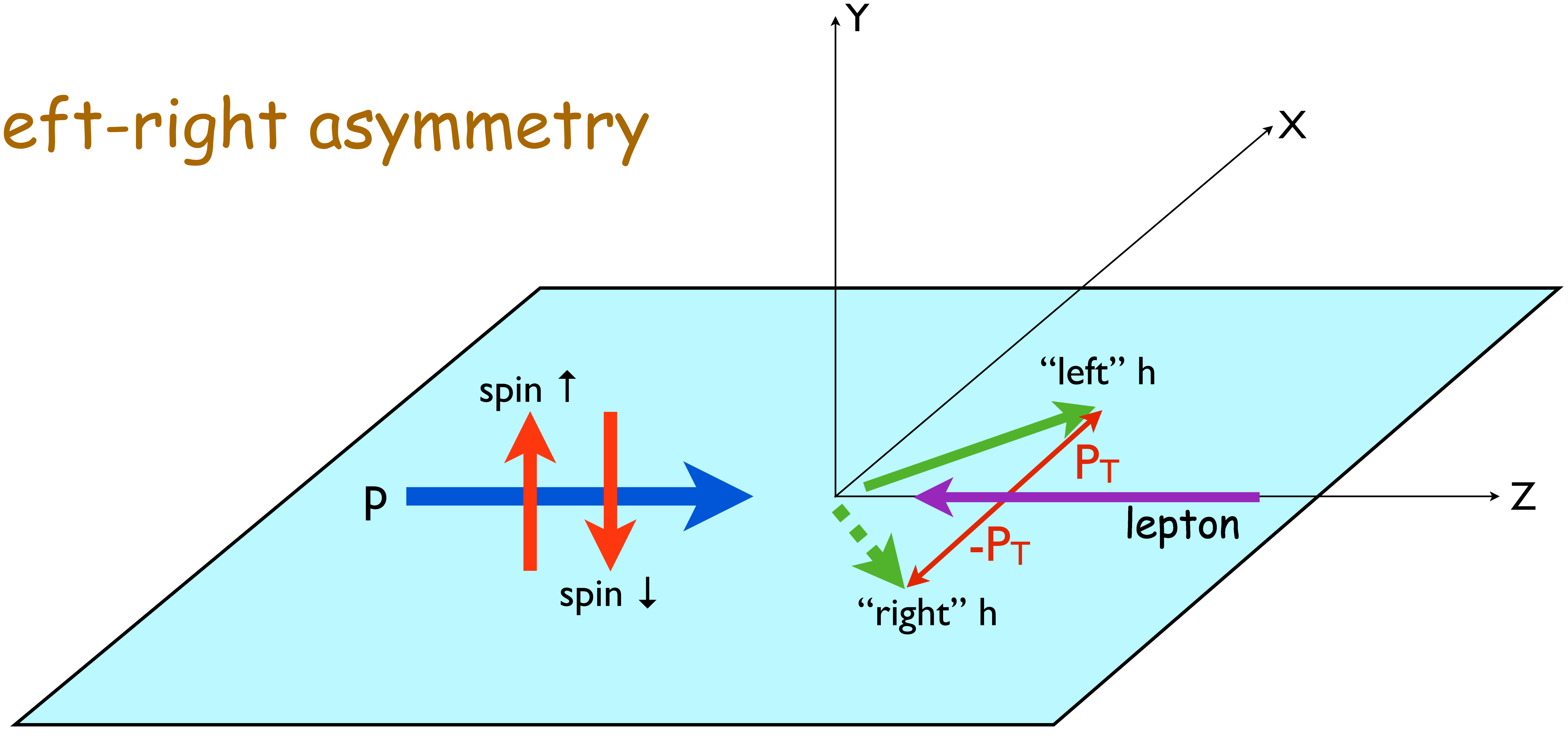
Which Sivers functions should we use?

Are there other contribution to AN in addition to Sivers?

....

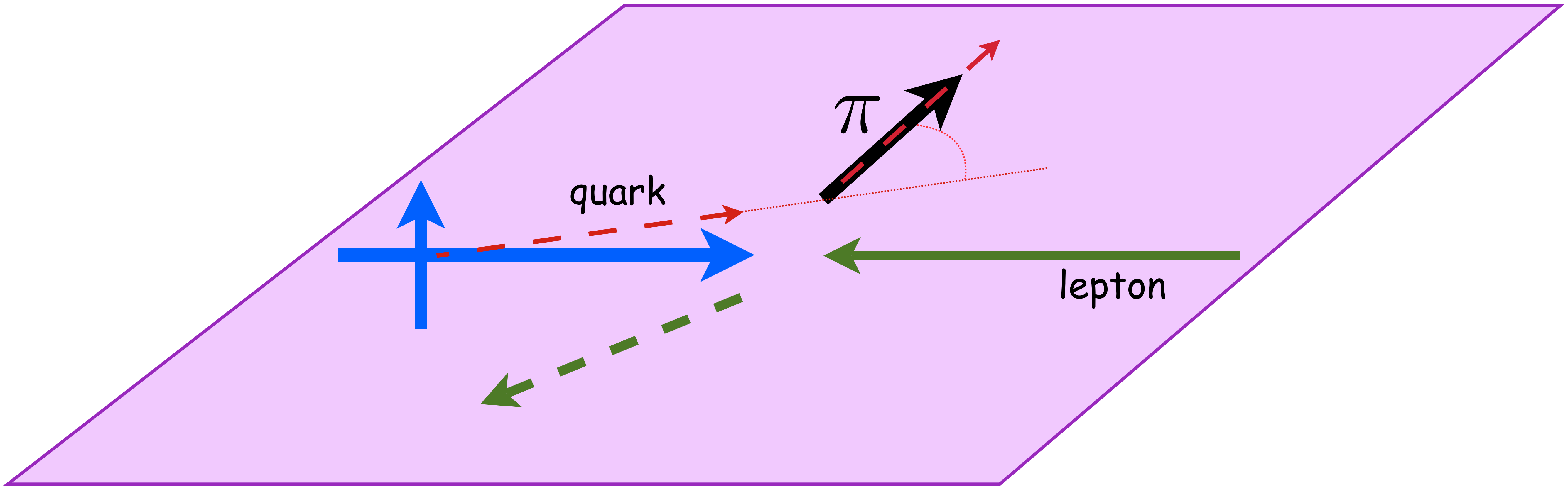
consider $p^{\uparrow} l \to h\, X$ large P_T processes
(one current jet events)

left-right asymmetry



$$A_N = \frac{d\sigma^{\uparrow}(\boldsymbol{P}_T) - d\sigma^{\downarrow}(\boldsymbol{P}_T)}{d\sigma^{\uparrow}(\boldsymbol{P}_T) + d\sigma^{\downarrow}(\boldsymbol{P}_T)} = \frac{d\sigma^{\uparrow}(\boldsymbol{P}_T) - d\sigma^{\uparrow}(-\boldsymbol{P}_T)}{2\, d\sigma^{\mathrm{unp}}(P_T)}$$

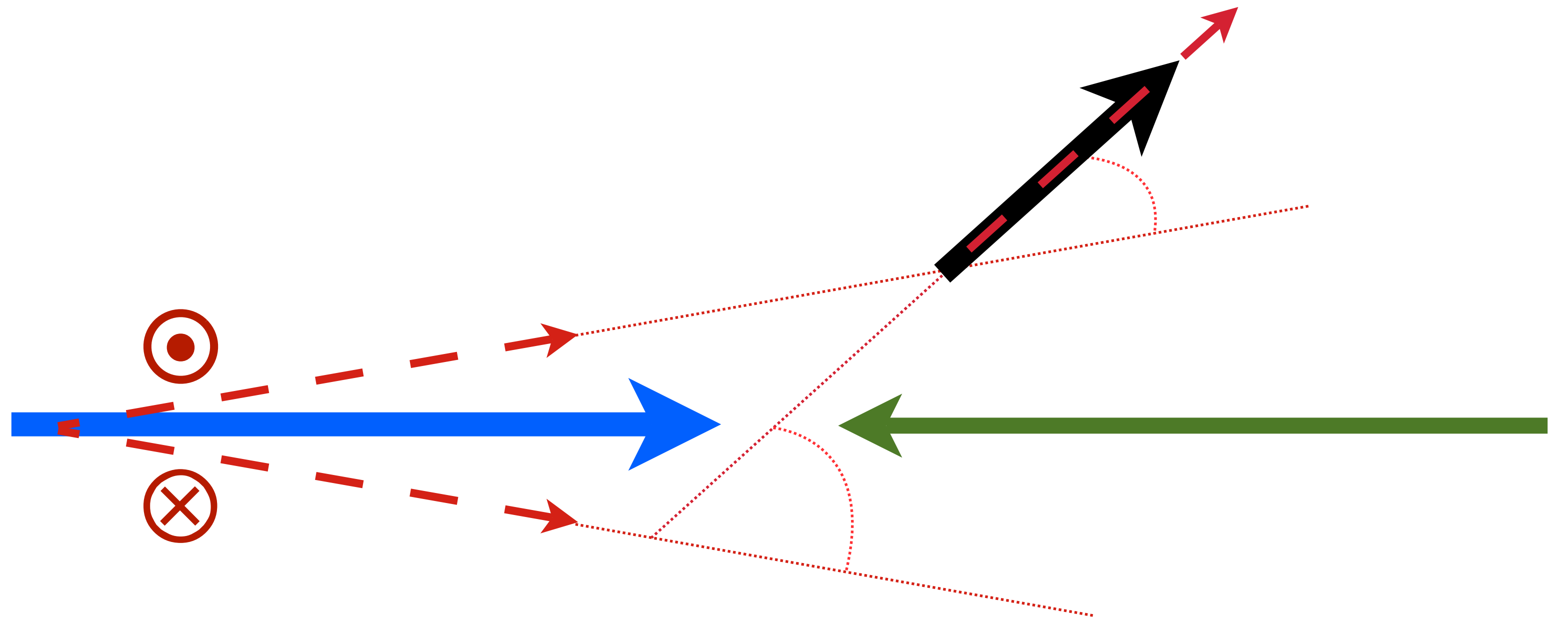
sivers effect at work



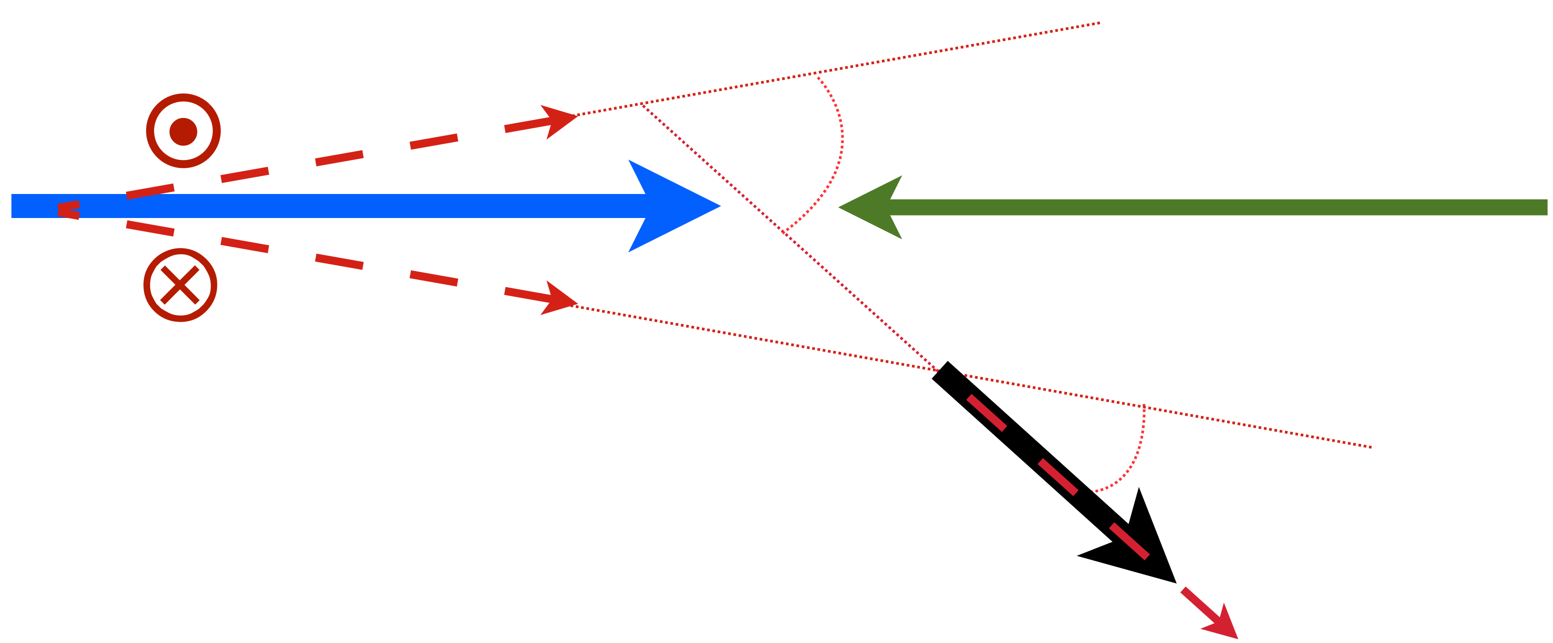
large P_T originated by large angle scattering $ql \to ql$,
large Q^2, $P_T > k_\perp$, $p_\perp$

QCD corrections should give two-jet events:

$$\gamma\, q \longrightarrow q\, q\,, \qquad \gamma\, g \longrightarrow q\, \bar{q}$$



left-right asymmetry



expect A_N to decrease as $k_\perp/P_T$

safe kinematical region

- high statistics at low p_T (around 0.5 GeV)

$\Rightarrow$ dominated by quasi-real photon exchange $\Rightarrow$ OUT of pQCD regime

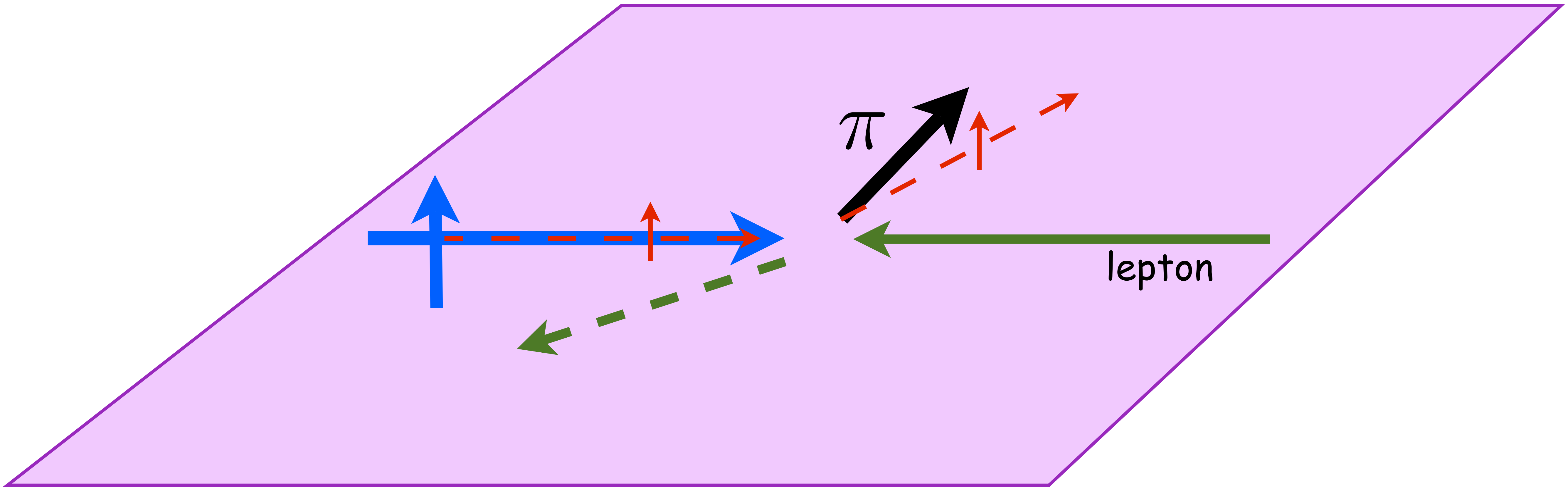
- $\Rightarrow$ consider larger p_T values ($x_F > 0 \equiv$ forward region of the proton):

$|t|_{\rm min}$ values

p_T	collinear		TMD	
	$x_F > 0$	$x_F < 0$	$x_F > 0$	$x_F < 0$
1.5 GeV	large	large	low	large
2.5 GeV	large	large	large	large

from talk of U. D'Alesio at DIS2009

Collins effect at work



$$
\begin{aligned}
D_{h/q,\boldsymbol{s}_q}(z,\boldsymbol{p}_\perp) &= D_{h/q}(z,p_\perp) + \frac{1}{2}\,\Delta^N D_{h/q^\uparrow}(z,p_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}_q\times\hat{\boldsymbol{p}}_\perp) \\
&= D_{h/q}(z,p_\perp) + \frac{p_\perp}{zM_h}\,H_1^{\perp q}(z,p_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}_q\times\hat{\boldsymbol{p}}_\perp)
\end{aligned}
$$

how does all that translate into a formula?

assume factorization:

$$\frac{E_h\, d\sigma^{(p,S)+\ell\to h+X}}{d^3\boldsymbol{P}_h} = \sum_{q,\{\lambda\}} \int \frac{dx\, dz}{16\,\pi^2 x\, z^2 s}\, d^2\boldsymbol{k}_\perp\, d^3\boldsymbol{p}_\perp\, \delta(\boldsymbol{p}_\perp \cdot \hat{\boldsymbol{p}}'_q)\, \delta(\hat{s}+\hat{t}+\hat{u})$$

$$\times \underbrace{\rho^{q/p,S}_{\lambda_q,\lambda'_q}\, \hat{f}_{q/p,S}(x,\boldsymbol{k}_\perp)}_{\text{TMD-PDFs}}\, \frac{1}{2}\, \hat{M}_{\lambda_q,\lambda\,;\lambda_q,\lambda}\, \hat{M}^*_{\lambda'_q,\lambda\,;\lambda'_q,\lambda}\, \underbrace{\hat{D}^{\lambda_h,\lambda_h}_{\lambda_q,\lambda'_q}(z,\boldsymbol{p}_\perp)}_{\text{TMD-FFs}}$$

$$|\hat{M}_{++;++}|^2 \equiv |\hat{M}^0_1|^2 = 64\,\pi^2\alpha^2 e_q^2\, \frac{\hat{s}^2}{\hat{t}^2}$$

$$|\hat{M}_{+-;+-}|^2 \equiv |\hat{M}^0_2|^2 = 64\,\pi^2\alpha^2 e_q^2\, \frac{\hat{u}^2}{\hat{t}^2}$$

$$\hat{M}_{++;++}\, \hat{M}^*_{-+;-+} = 64\,\pi^2\alpha^2 e_q^2\, \frac{\hat{s}(-\hat{u})}{\hat{t}^2}\, e^{-i(\phi-\phi')}$$

elementary interaction (at lowest order); phases due to non collinear, non planar configuration

$$A_N = \frac{\displaystyle\sum_{q,\{\lambda\}} \int \frac{dx\, dz}{16\,\pi^2 x\, z^2 s}\, d^2\boldsymbol{k}_\perp\, d^3\boldsymbol{p}_\perp\, \delta(\boldsymbol{p}_\perp \cdot \hat{\boldsymbol{p}}'_q)\, \delta(\hat{s}+\hat{t}+\hat{u}) \times [\Sigma(\uparrow) - \Sigma(\downarrow)]^{q\ell\to q\ell}}{\displaystyle\sum_{q,\{\lambda\}} \int \frac{dx\, dz}{16\,\pi^2 x\, z^2 s}\, d^2\boldsymbol{k}_\perp\, d^3\boldsymbol{p}_\perp\, \delta(\boldsymbol{p}_\perp \cdot \hat{\boldsymbol{p}}'_q)\, \delta(\hat{s}+\hat{t}+\hat{u}) \times [\Sigma(\uparrow) + \Sigma(\downarrow)]^{q\ell\to q\ell}}$$

$$\begin{aligned} \sum_{\{\lambda\}} [\Sigma(\uparrow) - \Sigma(\downarrow)]^{q\ell\to q\ell} \quad &= \quad \frac{1}{2}\, \overbrace{\Delta^N \hat{f}_{q/}(x, k_\perp) \cos\phi}^{\text{Sivers}} \left[\, |\hat{M}_1^0|^2 + |\hat{M}_2^0|^2 \right] \hat{D}_{h/q}(z, p_\perp) \\ &+ \quad h_1(x, k_\perp)\, \hat{M}_1^0 \hat{M}_2^0\, \underbrace{\Delta^N D_{h/q}(z, p_\perp)\, \cos(\phi' + \phi_h^H)}_{\text{Collins x phases}} \end{aligned}$$

$$\sum_{\{\lambda\}} [\Sigma(\uparrow) + \Sigma(\downarrow)]^{q\ell\to q\ell} = \hat{f}_{q/p}(x, k_\perp) \left[\, |\hat{M}_1^0|^2 + |\hat{M}_2^0|^2 \right] \hat{D}_{h/q}(z, p_\perp)$$

Even simpler: A_N for $p^\uparrow l \to$ jet X (only Sivers effect)

$$\frac{E_{jet}\, d\sigma^{(p,S)+\ell\to jet+X}}{d^3\boldsymbol{P}_{jet}} = \sum_{q,\{\lambda\}} \int \frac{dx}{16\,\pi^2 x\, s}\, d^2\boldsymbol{k}_\perp\, \delta(\hat{s}+\hat{t}+\hat{u}) \times \rho^{q/p,S}_{\lambda_q,\lambda'_q}\, \hat{f}_{q/p,S}(x,\boldsymbol{k}_\perp)\, \frac{1}{2}\, \hat{M}_{\lambda_q,\lambda\,;\lambda_q,\lambda}\, \hat{M}^*_{\lambda_q,\lambda\,;\lambda'_q,\lambda}$$

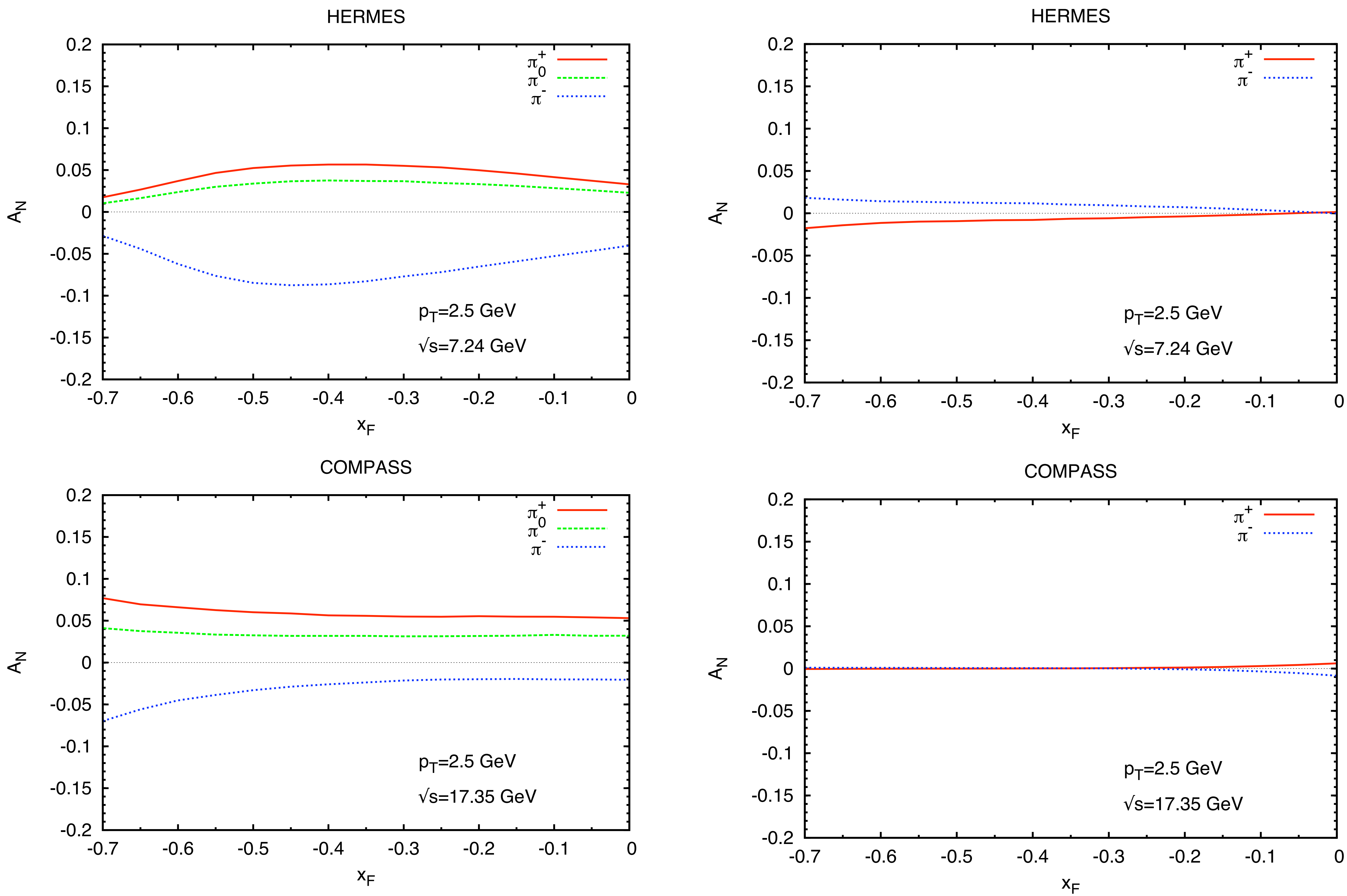
$$A_N^{jet} = \frac{\displaystyle\sum_{q,\{\lambda\}} \int \frac{dx}{16\,\pi^2 x\, s}\, d^2\boldsymbol{k}_\perp\, \delta(\hat{s}+\hat{t}+\hat{u}) \times [\Sigma(\uparrow)-\Sigma(\downarrow)]^{q\ell\to q\ell}_{jet}}{\displaystyle\sum_{q,\{\lambda\}} \int \frac{dx}{16\,\pi^2 x\, s}\, d^2\boldsymbol{k}_\perp\, \delta(\hat{s}+\hat{t}+\hat{u}) \times [\Sigma(\uparrow)+\Sigma(\downarrow)]^{q\ell\to q\ell}_{jet}}$$

$$\sum_{\{\lambda\}} [\Sigma(\uparrow)-\Sigma(\downarrow)]^{q\ell\to q\ell}_{jet} = \frac{1}{2}\, \Delta^N \hat{f}_{q/}(x,k_\perp)\cos\phi \left[\, |\hat{M}_1^0|^2 + |\hat{M}_2^0|^2 \right]$$

$$\sum_{\{\lambda\}} [\Sigma(\uparrow)+\Sigma(\downarrow)]^{q\ell\to q\ell}_{jet} = \hat{f}_{q/p}(x,k_\perp) \left[\, |\hat{M}_1^0|^2 + |\hat{M}_2^0|^2 \right]$$

A_N-Sivers

A_N-Collins



Sivers and Collins functions as extracted from SIDIS data

A_N in $p^\uparrow l \to h\, X$ or $p^\uparrow l \to$ jet X

most simple test of TMD factorization in one large scale processes

no problem with universality

might even look at h inside the jet (Collins effect), $p^\uparrow l \to$ h-jet X

maybe difficult with ongoing experiments

EIC, ENC, ...